RADIOACTIVITY

BY

EDWIN PLIMPTON ADAMS

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RADIOACTIVITY

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Electrophysics Committee

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Resolutions Adopted by the Board of Directors of the American Institute of Electrical Engineers May 20, 1913

Whereas, the American Institute of Electrical Engineers is greatly indebted to Professor Edwin Plimpton Adams for his admirable presentation of the subject of Radioactivity in the series of lectures delivered by him before the members of the Institute during the latter part of March and early in April, and

Whereas, the Institute, through the publication of these lectures in its PROCEEDINGS, is able to place before its entire membership a general survey of the history and important results of radioactive research and its bearing on modern electrical theory, be it

Resolved, that the Board of Directors of the Institute, recognizing the importance of this interesting field of research and its relation to electrical science, hereby tenders to Professor Adams its cordial thanks for the opportunity afforded by him of publishing for the benefit of the Institute membership a general discussion of this important subject, and, further, that the Board hereby expresses its appreciation of the able manner in which the subject was presented.

RADIOACTIVITY

BY EDWIN PLIMPTON ADAMS

LECTURE I

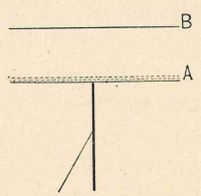
The science of radioactivity has now reached a stage in its development at which we can speak of it with a good deal of confidence. Among those who feel a keen interest in the recent developments of science, but who have not had time to follow them in detail, and it is to such that I was asked to address these lectures, there is a rather prevalent feeling that the discoveries in this branch of physics and chemistry have been of a revolutionary character. One often hears the opinion expressed that the discoveries in radioactivity have completely overthrown many of the theories that we had come to look upon as firmly established. In particular, I have often been asked about the validity of the principle of the conservation of energy—the fundamental principle of the physical sciences—in the light of the phenomena of radioactivity. Can we still build upon that principle? What I shall attempt in these lectures is to show how far our old notions of the constitution of matter are still valid, what modifications we must make in them, and where the physical sciences stand at present in the light of the discoveries that have been made during the 17 years that have elapsed since the discovery of radioactive phenomena. I hope to succeed in showing you that the results that have been obtained are much more constructive than destructive in their effect upon our views as to the constitution of matter. Instead of being revolutionary in their tendency they lead, viewed in a certain way, to a logical development of the physical sciences; for these discoveries give us information about the interior structure of the atom about which everything was largely conjecture. We are only at the beginning of what is bound to lead to a much fuller conception of atomic structure. The foundation for it has

been built up, and it is this foundation that I wish to describe to you.

The discovery of the property of radioactivity may be said to have had its inception in the discovery by Röntgen, in 1896, of the rays which bear his name. Guided by the similarity between the greenish yellow luminescence observed on the walls of a Röntgen ray bulb when the rays are produced and the greenish phosphorescence of certain uranium compounds after exposure to light, Becquerel sought a connection between these two phenomena. In the course of his experiments Becquerel found that uranium and its compounds produced effects very similar to those of the Röntgen rays—namely, a photographic plate completely shielded from ordinary light, by covering with black paper, was affected when the uranium was brought near in the same way that it would have been if exposed to ordinary light; and furthermore, the air in the neighborhood of the uranium became a conductor of electricity. But there is one striking difference between the effects produced by these two agents. For the Röntgen rays to produce them there must be a continuous supply of energy from outside to keep the electrical discharge in the bulb; while the production of these effects by the uranium was found to depend in no way upon previous illumination or any other external source of energy.

Becquerel thus discovered a new property of matter—the property of radioactivity, and it was an important question to determine whether this property was exhibited by other substances than uranium and its compounds.

In the first place it must be shown how the radioactivity of different substances may be compared. The property which is generally made use of for this purpose is that of rendering air a conductor of electricity. As the currents to be measured are very small, smaller than can be measured by a galvanometer, some form of electrometer is employed. The simplest is the gold leaf electroscope.



Let A and B be the plates of a condenser of capacity C. A known amount of the radioactive substance is spread on A. If charged to a difference of potential V the quantity of electricity on one of the plates is $C\ V$. The current flowing between the plates is

$$C\frac{dV}{dt} = i$$

Suppose that over a certain range of motion of the gold leaf it is known that a fall in its potential of a volts corresponds to a fall through θ degrees. Then a fall through ϕ degrees in a second will correspond to a current

$$i = \frac{a\ C}{\theta}\phi$$

The electric current through the air does not obey Ohm's law, but exhibits the phenomenon of saturation; *i.e.*, as the difference of potential is increased from 0, the current first increases nearly proportionately to the potential, rising to a nearly constant value which it keeps until the difference of potential is sufficient for a discharge to take place. As long as the difference of potential is greater than a certain value (100–200 volts in usual cases) the currents measured in this way will be nearly the same over a very wide range of potential difference.

Now Becquerel found that the activity of the different compounds of uranium was proportional to the amount of uranium contained in them. If the activity of metallic uranium be taken as unity, then the activities of the uranium compounds will be expressed by numbers less than unity.

Of the elements known at that time, only one other was found to have radioactive properties. Schmidt and, independently, Madame Curie, found that thorium and its compounds were radioactive.

Madame Curie's discovery of the radioactivity of thorium was made in the course of a systematic investigation, first, of all the known elements it was possible to secure, and then of a large number of minerals and rocks. She found that the activity of the uranium minerals was larger than was to have been expected from their uranium content. Thus a certain specimen of pitchblende, an oxide of uranium, had an activity nearly four times that of metallic uranium. An obvious deduction from this discovery was that these minerals contained one or more hitherto unknown substances, in minute proportions to have escaped discovery by chemical analysis and of correspondingly high radioactivity.

The method employed by Madame Curie to test this hypothesis was to subject a large quantity (one ton) of the residues from the mineral pitchblende, after the uranium had been extracted, to chemical analysis. It was found that the radioactivity of these

residues was four times as great as that of metallic uranium, from which it was concluded that the greater part of the conjectured substance was contained in them. In brief, the method of attack consisted in measuring the activity of all the products of a chemical separation in order to find which one of them included the looked-for substance. This one was then subjected to further separation and the process continued. The difficulties in this precedure were great, for owing to the phenomenon of induced or excited radioactivity, of which more will be said later, there was some uncertainty in the earlier stages of the separation as to which product contained the radioactive substance; and, in addition, it was found that there were several unknown substances, strongly radioactive, of different chemical behavior, which complicated the search very considerably. But we shall see that all these substances are closely related so that for the present it will be sufficient to speak of only one of them.

It was finally found that the product of separation containing the barium was enormously more active than any of the other products. No chemical method of making a further separation could be found, and so recourse was had to an assumed difference in solubility between the barium salt and the unknown substance. From a solution of two different substances that one of less solubility will crystallize first. The barium in the form of barium chloride was allowed to crystallize and the first crystals formed were found to be decidedly more active than those found later.

One of the characteristics of an element is the possession of a definite spectrum. When this very active barium chloride was examined spectroscopically before the fractional crystallization began, only the lines due to barium appeared. As the process of fractional crystallization proceeded new lines appeared, the barium lines grew fainter, until after a number of crystallizations the original barium spectral lines had disappeared, and a new spectrum had taken their place. This in itself was sufficient to prove the discovery of a new element, to which the name radium was given.

From a ton of the original material 120 milligrams of radium chloride were obtained in the way indicated. Its activity was estimated by Madame Curie at about a million times that of uranium. Madame Curie also succeeded in determining the atomic weight of the new element radium. The first number obtained, 225, has been corrected by more recent work, so that now 226.4 is accepted as the atomic weight of radium, taking oxygen = 16.

There being a greater difference in the solubilities of radium and barium bromides than of their chlorides, radium is now generally prepared in the form of the bromide.

Madame Curie and Debierne have lately been successful in isolating the metal radium itself by electrolysis with a mercury cathode, thus forming a radium amalgam. This amalgam was then distilled in an atmosphere of hydrogen. The mercury was completely driven off at a temperature of 700 deg. and the remaining substance, practically pure radium, had a shining white metallic luster. It rapidly turned black in air, and decomposed water. Chemically its behavior was thus similar to that of metallic barium.

We have now traced, very briefly, the processes leading to the discovery of this new element radium, and we must now study the physical properties of it in greater detail. We have seen that one of its most striking properties is that of rendering the air surrounding it a conductor of electricity. It will therefore be well to preface this study by a brief resumé of the theory of ionization of gases.

A gas in its normal condition is a non-conductor of electricity. It may be made a conductor by various agents, among others, the passage through it of Röntgen rays, of ultra-violet light, and, we have seen, by radioactive substances. But it was through the study of the electric discharge in vacuum tubes that our knowledge of the way in which gases become conductors of electricity came; and to Sir Joseph J. Thomson belongs the credit of having developed a consistent theory which has proved of the greatest service in all the recent developments of electric theory.

The leading idea in Thomson's theory is that negatively charged corpuscles—or electrons—are shot out from the cathode; that these corpuscles by their collisions with the neutral molecules of the gas ionize them; that is, split them up into positive and negative parts; the positive ions travel towards the negative electrode, the cathode, and the negative ions towards the positive electrode, the anode. We thus have a double transport of electricity through the gas—positive electricity in one direction and negative electricity in the opposite direction. This constitutes an electric current, flowing in the direction of the positive ions. The path of the cathode rays, the stream of corpuscles shot out from the cathode, is made visible by the light which is produced in the ionization of the gas molecules, and there is also

a greenish yellow luminescence produced where the corpuscles strike the walls of the tube. An obstacle placed in the path of the cathode particles casts a shadow on the walls of the tube. By placing a diaphragm with a small opening in front of the cathode, a narrow beam of the cathode rays may be separated. When a magnet is brought near, the beam is deflected in the direction that a stream of negatively charged particles shot out from the cathode should be. The negative charges carried by these corpuscles may also be demonstrated by bending the beam into a vessel connected to an electrometer which becomes negatively charged. In short, every test that may be applied shows that the cathode rays are a stream of negatively electrified corpuscles. The cathode particles have one striking property which at first caused many investigators to doubt their material nature. This is their ability to penetrate thin sheets of metal and other substances. But now that we know their very high velocity, this property is not so surprising. The sudden increase in the electric current through a gas which occurs when the potential difference rises to a certain value, the "sparking potential," receives a ready explanation in this theory. The ions produced from the gas molecules are under the influence of the electric field. If the electric field is strong enough it will give the ions a sufficiently high velocity so that they become ionizing agents themselves—producing fresh ions by their collisions with the molecules of the gas.

The real confirmation of the hypothesis of the material nature of the cathode particles was furnished by actual measurements of their velocity, the charges they carry, and their mass. As the same methods have since been employed in the study of the radiations from radioactive substances, we may well devote a little time in considering the principles involved in such measurements.

Let us suppose that we have a corpuscle of mass m, charged with e units of electricity and moving in a straight line with uniform velocity v. As proved by Rowland's classic experiment, a charged body in motion is equivalent to an electric current. Suppose that a magnetic field of intensity H is set up in a direction at right angles to the motion of the corpuscle. If there were an electric current, i, flowing along a wire in the path of the corpuscle, we know that on each element of length ds of the current there would be a mechanical force $H\,i\,ds$, this force being perpendicular both to ds and H. The current element $i\,ds$ is to be replaced

by the product of the charge and its velocity, $e\,v$. So that the force acting on the corpuscle at right angles to v is $H\,e\,v$. The acceleration normal to the velocity is v^2/ρ where ρ is the radius of curvature, or in our case the radius of the circle into which the path of the corpuscles is bent. We thus have

$$H\,e\,v = \frac{m\,v^2}{\rho} \qquad (1)$$

Let us next suppose that an electric field of intensity X is set up parallel to the magnetic field, at right angles to v and to H. This exerts a force $e\,X$ on the corpuscles, and by varying X we can make this force just balance the force exerted by the magnetic field so that the corpuscle will be undeflected. We then have $H\,e\,v = e\,X$

or
$$v = \frac{X}{H} \qquad (2)$$

which determines the velocity of the corpuscles, and by (1)

$$\frac{e}{m} = \frac{X}{H^2\,\rho} \qquad (3)$$

which determines the ratio of the charge to the mass of the corpuscle. In these expressions X and H may be determined by the usual methods of measuring electric and magnetic forces. To determine ρ, it is necessary to measure the displacement of the spot of light made by the narrow beam of cathode rays on a phosphorescent screen when the magnetic field is applied; by geometry the radius of the circular path may then be found.

The velocity of the cathode particles found in this way was as high as 1.2×10^{10} cm. per second, roughly one third the velocity of light. Probably the most accurate value of e/m found by this method is 1.8×10^{7} when the charge is measured in electromagnetic units. It is interesting to compare this with the ratio e/m for the charge carried by a hydrogen atom in the electrolysis of water. Let N be the number of molecules in one cu. cm. of gas at 0 deg. cent. and at 760 mm. of mercury. If e is the charge on an atom of hydrogen $2\,N\,e$ is the whole charge in one cu. cm. One electromagnetic unit of electricity liberates 1.04×10^{-4} grams of hydrogen. If m is the mass of hydrogen atom $2\,m\,N$ is the mass of one cu. cm. of hydrogen. So that

$$\frac{e}{m} = 9.6 \times 10^{3}$$

We shall show that there is strong reason for believing that the charge on a corpuscle is the same as the charge carried by an atom of hydrogen in electrolysis. The mass of the hydrogen atom, which was, up to the time of the discovery of corpuscles, the smallest mass known, is thus seen to be about 1800 times greater than the mass of a corpuscle.

Measurement of the Charge Carried by Ions

We have seen that the cathode particles have the power of ionizing gases through which they pass. This process consists in the splitting up of an atom or molecule into a positively and a negatively charged ion. Now it was discovered by C.T.R. Wilson that these ions act as centers of condensation for water vapor. In perfectly dust-free air, saturated with water vapor, no cloud of water drops will form unless the air is suddenly cooled by an expansion to something like eight times its initial volume. But if dust is present very much smaller expansions will suffice to produce a visible cloud on expansion. Wilson discovered that in dust-free ionized air sudden expansion to 1.25 the original volume was sufficient to produce a cloud in the air, each ion presumably becoming the nucleus of a water drop. These drops fall under gravity and their rate of fall may be determined from the rate of subsidence of the top of the cloud after the expansion has taken place. A calculation, by Stokes, gives as the rate of fall of a sphere in a fluid

$$v = \frac{2}{9}\frac{g\,a^2\,\rho}{\mu}$$

g being the acceleration due to gravity, a the radius of the drop, μ the coefficient of viscosity of the fluid, air in our case, and ρ the density of the sphere. This expression thus enables us to determine the radius of the water drops. The whole volume, q, of the water vapor deposited per unit volume may easily be determined by thermodynamical methods; and

$$q = \frac{4}{3}\,n\,\pi\,a^3$$

where n is the number of drops per unit volume. This enables us to determine n, which, if we assume that each ion acts as a nucleus for one drop, gives us the number of ions per cubic centimeter. The total charge carried by all the ions of one sign

may be determined by measuring the current through the air when a potential difference is applied; then the charge on a single ion is deduced at once.

This method was modified by H. A. Wilson so as to eliminate many of the uncertainties inherent in Thomson's original method. The cloud was produced between the plates of a parallel plate condenser and the rate of motion of the top of it observed alternately when under the influence of gravity only, and when in addition an electric field was applied. The force on the drop due to the electric field is $X\,e$ and due to gravity

$$\frac{4}{3}\,\pi\,\rho\,g\,a^3$$

$$\frac{X\,e + \frac{4}{3}\,\pi\,\rho\,g\,a^3}{\frac{4}{3}\,\pi\,\rho\,g\,a^3} = \frac{v_1}{v}$$

v_1 is the velocity when an electric force is applied; v, with no electric force.

$$v = \frac{2}{9}\frac{g\,a^2\,\rho}{\mu}$$

$$e = \sqrt{2}\,g\,\pi\sqrt{\frac{\mu^3}{g\,\rho}}\,\frac{v^{3/2}\,(v_1 - v)}{X\,v}$$

Another modification, in which the motion of a single drop is watched, was made by R. A. Millikan, and the results of his measurements are probably the most accurate that we have. In the two methods we have sketched the cloud must be observed immediately after its formation, since it rapidly disappears by evaporation. Millikan used oil drops, formed by means of an atomizer and blown into a chamber from which they dropped through an opening into the space between the plates of a parallel plate condenser. This space could be made airtight after a drop had fallen into it so as to prevent air currents disturbing the motion of the drop. The oil drop was specially illuminated and was observed through a telescope. In its formation the drop became charged with frictional electricity so that its motion could be controlled by the electric field in the air condenser. The evaporation from it was so small that a single drop could be

observed for several hours. An ionizing agent, Röntgen rays or radium rays, acted on the air in the condenser and the oil drop occasionally picked up an ion. The instant it did so its motion suddenly changed, and from the change in its motion the magnitude and sign of the charge it had picked up could be found. In addition to the more accurate method of observing, Millikan employed a correction to Stokes's formula for the rate of fall of a sphere in air which was developed by Cunningham for the case of very small spheres. The results of Millikan's experiments were that the charges on the oil drops were always exact multiples of an elementary charge, that is, the oil drop picked up one or more of these elementary charges. Its magnitude was found to be $e = 4.774 \times 10^{-10}$ in electrostatic units.

We have seen that determinations of the velocity and the ratio e/m have been made directly on the corpuscles forming the cathode rays. On the other hand determinations of e, the elementary charge, have been made only on ions, both positive and negative, which are formed by various ionizing agents. The evidence that the cathode particles carry this elementary charge is perhaps not conclusive, but the fact that the ratio e/m is found to be the same for the corpuscles however they are produced, and that ionization in certain cases must be considered as the result of a corpuscle entering into a neutral atom, thus giving the ion the charge of the corpuscle, gives us very strong reasons for believing that all corpuscles carry this negative elementary charge.

The accurate determination of the charge on an ion leads to a knowledge of many important physical constants. It is known by experiment that when 1 electromagnetic unit of electricity is passed through water 1.04×10^{-4} grams of hydrogen are liberated. If N is the number of molecules in a cubic centimeter of any gas at a pressure of 760 mm. of mercury, and at 0 deg. cent. temperature, ρ the density of hydrogen, and e the charge on a hydrogen atom in electrolysis,

$$2 \frac{N e}{\rho} 1.04 \times 10^{-4} = 1$$

or

$$e = \frac{\rho \, 10^4}{2.08 \, N}$$

Now N may be estimated from the results of the kinetic theory of gases. The value of N so obtained is, on the average,

$$N = 3 \times 10^{19}$$
$$\rho = 9 \times 10^{-5}$$

from which it follows that

$$e = 1.4 \times 10^{-20}$$

in electromagnetic units or

$$4.2 \times 10^{-10}$$

in electrostatic units.

This is so near the value of the charge in the ion, determined in the way sketched above, that we are led to believe that the charge on the ion of hydrogen in electrolysis is equal to the elementary charge determined on gaseous ions. As the latter determination is one in which we have more confidence than estimates based upon the kinetic theory of gases, we are led to determine N from the known value of e. This gives

$$N = 2.7 \times 10^{-19}$$

Now if m is the mass of an atom of hydrogen

$$m = \frac{\rho}{2 \, N}$$

Thus the mass of an atom of hydrogen is

$$1.67 \times 10^{-24}$$

and from this the mass of the atom of any element can be determined from its atomic weight in terms of hydrogen as unity.

Radiations from Radioactive Substances

We now are going to consider the radiations from radioactive substances in particular. To trace in detail the course of the discovery of the nature of these radiations would require too much time, and so we must limit ourselves to an outline of what is known about them today and the evidence upon which our knowledge rests.

Beta Rays. We consider first the so-called beta rays. These rays are in all respects identical with the corpuscles forming the cathode rays in a vacuum tube, except that, among them, there are some that travel with very much higher velocities than any that can be produced in a discharge tube. Their equivalence to the cathode corpuscles is shown by measurements of e/m and v for them—measurements that are made in exactly the same way, by magnetic and electric deviation, as for the cathode particles. Further, the charges on the ions produced by them are also the same as the charges on the ions produced in any other way. Later

on we shall have to speak of a variation of the ratio e/m with the velocity, but it is a variation which is conditioned only by the velocity and does not indicate that these corpuscles themselves are in any way different from the others.

To show the penetrating power of the beta rays, as well as the charge they carry, Strutt devised a striking experiment. A quantity of radium in a thin-walled glass tube was supported by an insulator inside a highly exhausted bulb. The beta rays penetrated the glass tube, leaving the radium positively charged. A pair of gold leaves was carried by the glass tube containing the radium, and by means of a wire sealed into this tube the gold leaves were kept at the same potential as the radium. As the radium gained a positive charge by the expulsion of the negative corpuscles the gold leaves diverged until they touched the walls of the bulb which were coated with tinfoil, connected to earth. They then discharged to earth, and collapsed. This process repeated itself over and over again.

On passing through matter the velocity of the beta particles is reduced. For this reason, even if it should be assumed that all the beta particles from a given radioactive substance are emitted with the same velocity, those which are emitted from a thick layer of substance will have different velocities, since they pass through different thicknesses of the substance. The most rapidly moving beta particles have velocities very near the velocity of light, differing from the latter by about one per cent. It is not surprising, therefore, that they should be able to penetrate considerable thicknesses of solid matter. W. Wilson found that on passing through 2 mm. of aluminum the velocity was reduced from 2.86×10^{10} cm. per second to 2.00×10^{10} cm. per second.

In their passage through matter the beta rays lose their energy. In gases this loss of energy is caused by ionization, as it requires work to form ions from neutral atoms. In solids, also, there is good evidence that their conductivity is increased by the ions formed in them by the beta rays. The rays thus have their energy decreased so much that ultimately they are unable to ionize the atoms through which they pass.

Some very remarkable results have recently been obtained by C. T. R. Wilson, who succeeded in photographing the paths of the beta particles through gases. In passing through a gas positive and negative ions are formed, and these ions act as centers of condensation of water vapor. The path of a beta particle is thus marked out by the water drops formed on the ions which it pro-

PLATE XXIV
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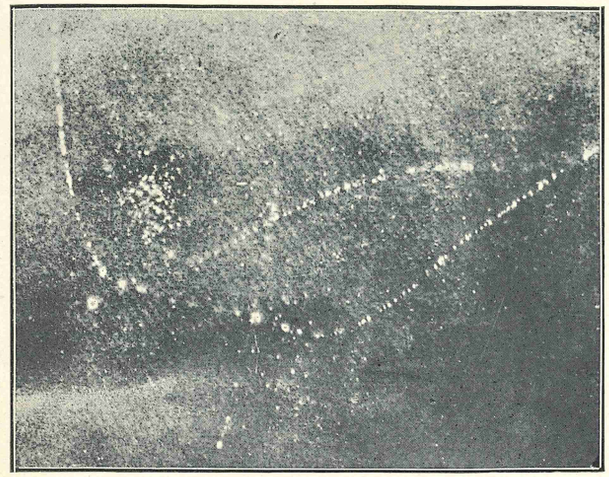
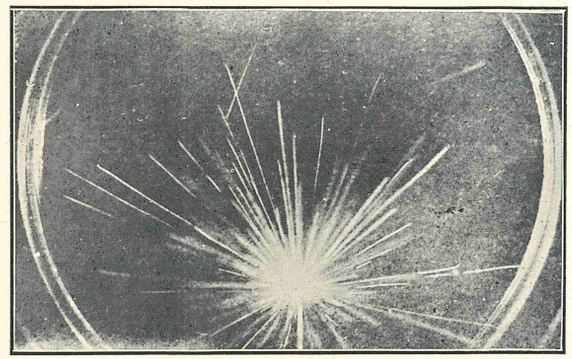


PATHS OF BETA PARTICLES [ADAMS]



PATHS OF ALPHA PARTICLES [ADAMS]

duces, and with great ingenuity and experimental skill Mr. Wilson has succeeded in obtaining photographs of these trails of water drops. Two of his photographs are reproduced here. I am indebted to Mr. Wilson for permission to use these photographs. The beginnings of the trails are quite straight and very faint, showing that the velocity of the beta particle is so high that it passes through the molecules without ionizing many of them. As the velocity decreases, more ions are formed, and the path of the beta particle becomes curved as a result of deflections arising from collisions with the molecules.

Alpha Rays. Another type of radiation emitted by radioactive substance is made up of the alpha rays. These differ from the beta rays, first, in that they are positively charged, carrying charges double that of the beta particles, and in that their mass is that of an atom of helium. They produce ionizing and photographic effects like the beta particles, but their very much larger mass and their lower velocity account for their smaller penetrating power.

The alpha particles from any given radioactive product are all emitted with the same velocity. This makes the study of their absorption in passing through matter simpler than for the beta particles, which are emitted in groups having different velocities. The fastest particles are emitted with a velocity of 2.22×10^9 cm. per second while the slowest have an initial velocity of 1.45×10^9.

It was found by Bragg that the alpha particles on traversing matter are slowed down, and when their velocity falls below a certain value they lose their ionizing and photographic power. The "stopping power" of various substances is found to be proportional to the square root of the atomic weight. For chemical compounds, it is proportional to the sum of the square roots of the weights of the atoms contained in the molecule.

An interesting effect produced by alpha rays is the so-called scintillation phenomenon observed when the alpha particles strike against a screen of phosphorescent zinc sulphide. The screen appears, when looked at through a magnifying glass, to be dotted over with points of light, which come and go in a wholly irregular manner. This effect is probably caused by the mechanical impacts of the alpha particles producing changes in the crystalline structure of the zinc sulphide—analogous to the glow observed when a lump of sugar is broken in the dark. It is found that when the velocity of the alpha particles falls below its limiting value for producing ionizing and photographic effects, the scintillations

also cease. These scintillations may be counted, and, assuming that each point of light is caused by the impact of one alpha particle, an estimate may be made of the rate of emission of alpha particles from various radioactive substances. But a more certain method of arriving at the same result was devised by Rutherford. A small opening was made in a chamber in which a strong electric field was maintained. The alpha particles are shot out in all directions from a radioactive substance, so that the ratio of those entering the opening in a given time to the whole number shot out in the same time was known from the geometry of the arrangement. On entering the chamber the alpha particles produced ions and thus an electric current was suddenly started in the chamber, which disappeared very quickly as the ions were removed by the electric field. Thus the entrance of each alpha particle into the chamber was marked by a sudden rise in the current flowing through it, and this was made known by the kick of the electrometer needle used to measure the current. The number of kicks in a given time gave the number of alpha particles entering the chamber in that time, and from this the whole number of alpha particles emitted could be deduced. As a single alpha particle does not produce ions enough to give a current which can be detected, the current was multipled by fresh ions produced by the action of the strong electric field on those already present.

Knowing now the whole number of alpha particles emitted from a radioactive substance, the charge on each is known as soon as we know the whole charge carried by the particles. Measurements of this kind have been made by Rutherford and others, and the results show that the alpha particle carries a charge opposite in sign but double the amount of the charge carried by the beta particle, or electron.

From the deflection of a beam of alpha particles in an electric and a magnetic field the ratio e/m, and the velocity v, have been determined. Knowing now the charge, e, the mass of a single alpha particle is known at once. The ratio e/m is the same for the alpha particles from all the radioactive substances, while their velocity is different. In this way it is found that the alpha particle has a mass equal to four times the mass of the hydrogen atom. This is very nearly the mass of the helium atom and it thus seemed that the alpha particle was a helium atom which had lost two negative corpuscles, leaving it effectively charged with a double positive charge. This hypothesis was put to the

PLATE XXV
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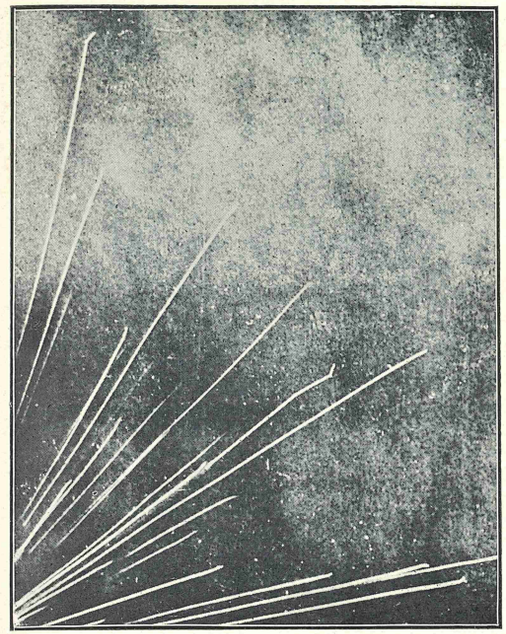
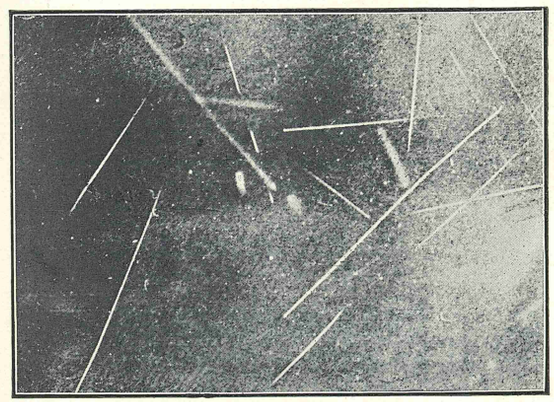
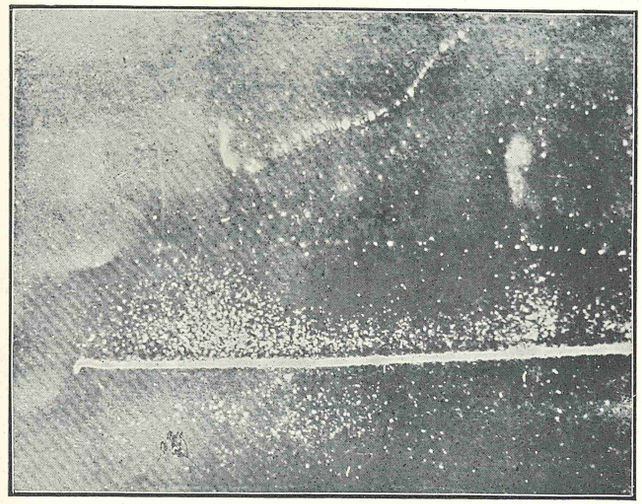


PATHS OF ALPHA PARTICLES [ADAMS]



PATHS OF ALPHA PARTICLES [ADAMS]



PATHS OF BETA PARTICLES [ADAMS]

The broad line is the path of an alpha particle.

test by Rutherford. The alpha particles were allowed to penetrate through the very thin walls of a glass tube into a highly exhausted tube through which an electric discharge could be passed. By examining its spectrum the nature of the gas, if any, which collected in the tube could be determined. In a few days the whole spectrum of helium appeared. Control experiments precluded any other possibility than that the alpha particles, shot through the walls of the tube, and having their charge neutralized, became helium atoms. The special significance of this fact will be spoken of later when we come to consider the disintegration theory of radioactivity.

The recent experiments of C. T. R. Wilson, making visible the tracks of the beta particles through a gas by photographing the water vapor which condenses on the ions produced, have been spoken of. He obtained similar results with the alpha particles. His photographs, some of which are shown here, are even more striking than those obtained with the beta particles. The alpha particle, owing to its greater energy, is a much more efficient ionizer than the beta particle so that its track through a gas is marked out by many more ions on which the water drops collect. It will be seen that these tracks end abruptly, and this is accounted for by the fact that they have a definite range, beyond which their ionizing power ceases. Many of the tracks show a bend toward their end. This is probably the result of the reduction in their velocity which makes them more easily deflected from their straight line motion by collisions with the molecules.

Gamma Rays. The third distinctive type of radiation emitted by radioactive substances is the gamma radiation. There is no direct evidence, as in the case of the alpha and beta rays, that the gamma rays are formed of charged particles. The gamma rays produce photographic and ionizing effects; their most striking property is their relatively enormous penetrating power. A thickness of about two millimeters of lead is sufficient to absorb all the alpha and beta particles emitted by radium. Effects produced by gamma rays have been observed after they passed through 30 cm. of iron.

To account for the gamma rays there are two theories we must consider. The first is the ether pulse theory which was originated by Stokes to account for the Röntgen rays. When a charged particle is in uniform motion through the ether there is no radiation of energy from it. Once get it moving and it will continue to move in a straight line with constant velocity. Accompanying

a charged particle at rest, there is an electric field which is everywhere directed along the radius drawn from the particle. In other words, lines of force go out from it, if positive, and enter it, if negative, equally distributed in all directions. There is no magnetic force while the particle is at rest. Now suppose the particle moves with uniform velocity in a straight line. It carries its lines of force with it, and as long as the velocity is small there is not much change from the equal distribution of lines in all directions. A charged particle in motion acts as an element of current; so that there is a magnetic field accompanying it. The magnetic force is at every point perpendicular both to the direction of motion and to the line drawn from the particle to the point. It is thus everywhere perpendicular to the electric force. Now, for higher velocities, the lines of electric and magnetic force crowd towards the equatorial plane, always at right angles to each other. For a velocity equal to that of light the electric and magnetic forces would all be concentrated in the equatorial plane.

Suppose now that a charged particle, moving with a velocity very nearly equal to that of light, is brought to rest within a very short distance by collision with an atom or by any other means. Just before its collision it carried a field of electric and magnetic force with it and this field was concentrated near the equatorial plane. Now suppose that the corpuscle is brought to rest in a very short distance. A pulse of intense electric and magnetic forces, at right angles to each other, spreads away from the corpuscle with the velocity of light, the direction of propagation being normal to the electric and magnetic forces. The thickness of this pulse is proportional to the distance in which the stopping took place, that is, to its acceleration. A succession of such pulses arising from the stopping of many corpuscles will thus give rise to electromagnetic waves in the ether which differ in no respect from waves of light except that the wave length is much less than that corresponding to light of the shortest wave length that we know anything of. On this view, the gamma rays from radioactive substances and the Röntgen rays are identical in their nature. Differences in effects produced by these two radiations are to be expected, since the beta rays, the origin of the gamma rays, have velocities which are much greater than the cathode rays which give rise to the Röntgen rays.

The other view as to the nature of gamma rays is due to Bragg. He regards the gamma rays as made up of material particles, a

negative corpuscle united to an equal positive charge, so that the combination is neutral electrically, the whole travelling with a velocity very nearly equal to that of light. This view of the gamma rays explains as well as the pulse theory the absence of any deflection of the gamma rays by electric or magnetic fields; it was originated by Bragg to account for certain dissymmetries on the incident and emergent sides of matter through which the rays pass—effects which are difficult to account for on the ether pulse theory. The study of the whole matter is greatly complicated by the secondary rays produced when gamma rays fall upon matter; these secondary rays are partly secondary gamma rays and partly secondary beta rays.

On the whole, the evidence seems to favor the ether pulse theory. Recent experiments by Laue and others seem to show the existence of diffraction effects when Röntgen rays pass through certain crystals. Whatever view we take of the gamma rays it seems well established that the Röntgen rays and the gamma rays are of the same nature. In the experiments referred to, a narrow beam of Röntgen rays was passed through a thin plate of a crystal, and the rays then fell on a photographic plate. In addition to the central spot produced by the rays directly transmitted, there were other spots arranged in more or less concentric circles around it. If we suppose, as we must, that in a crystal the molecules are regularly spaced, then a crystal plate will act as a diffraction grating. On the view that the Röntgen rays are ether pulses, these results receive a satisfactory explanation, while it would be difficult to explain them on any other view of the Röntgen rays. Accepting this view, estimates of the wave length of the Röntgen rays gave numbers in the neighborhood of 10^{-9} centimeters, about what was to be expected from the mode of their production.

LECTURE II

Introduction

It has been suggested to me that the meanings of some of the terms employed in the first lecture were rather uncertain to some of the audience, and the following chart has been prepared which may help to keep in mind the particular meanings of the terms employed throughout the lecture.

Cathode Particle **Beta Particle** **Corpuscle** **Electron**	A negatively charged particle, known only in motion, carrying the elementary electric charge: $e = 4.774 \times 10^{-10}$
Ion	A general term for a charged atom or molecule, or a cluster of atoms or molecules. May be charged either positively or negatively.
Alpha Particle	A positively charged atom of helium, carrying double the elementary charge, e.
Gamma Rays	Probably ether pulses produced by accelerations of the beta particles. Like Röntgen rays.

The four terms: cathode particle, beta particle, corpuscle, electron, all mean exactly the same thing. The distinction between them arises from the fact that the particles appear under different conditions. In the first place, the cathode particle is so called because it appears as if it were shot out from the cathode in a vacuum tube when an electric discharge is sent through. The beta particle is emitted by radioactive substances; the corpuscle and electron, which mean exactly the same, are general terms for both of these particles, and they are used when we wish to speak of them in general.

You will notice that I have not said anything on the chart in regard to the mass of these particles. This subject we shall have to come back to in the next lecture; but, roughly speaking, we can say that the mass of one of these particles is 1/2000 of the mass of the hydrogen atom; the hydrogen atom was, up to the discovery of these particles, the smallest known mass. Where I have used the word " atom," I mean exactly what chemists have always considered the atom to be; that is, the smallest mass which enters into chemical combinations.

Ion is a general term for any charged particle; frequently it is employed when the cathode or beta particle is meant. But usually by ion we mean a charged atom, or molecule, or a cluster of atoms or molecules which stick together around a central charge, which may be either positive or negative. Thus in the electrolysis of liquids, the current is carried by positive ions moving in one direction and negative ions moving in the opposite direction.

The alpha particle, about which we spoke last week, is a positively charged atom of helium; its mass is four times the mass of the hydrogen atom, and it carries a charge which is twice that of the cathode particle.

In regard to gamma rays, we saw last week that there is a good deal of evidence that they are electromagnetic disturbances, in every respect similar to light waves, except that their wave length is very much shorter than the wave length of any known light—something of the order of 1/1000 of the wave length of the shortest waves with which we are familiar.

The Disintegration Theory of Radioactivity

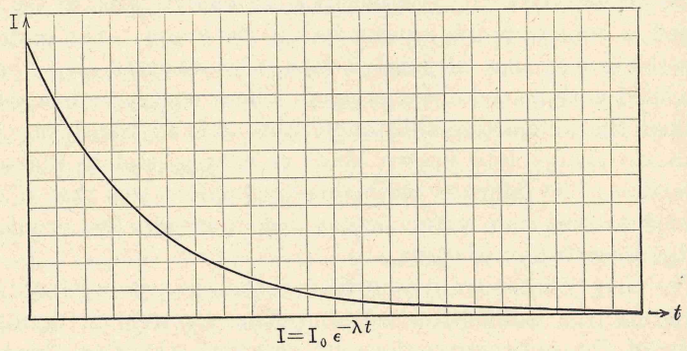
We have now given a brief account of the discovery of radioactive substances and of the chief characteristics of the radiations emitted by them. We proceed to consider an explanation of radioactive phenomena.

The most striking fact connected with the early study of radioactivity was the apparently continual emission of relatively large amounts of energy with no evident source of this energy. If the principle of the conservation of energy was to be retained, a source of this energy had to be found. The earliest hypothesis was that of Lord Kelvin, who assumed that space was filled with an unknown type of radiant energy and in some manner the radioactive substances were able to transform this unknown energy into known kinds of energy, and so make it apparent. The difficulty with this explanation was that it explained nothing, but merely let us keep formally the principle of the conservation of energy.

The clue to what we now believe to be the true explanation of radioactive phenomena was furnished by a more detailed study of the radioactive element, uranium—the first element which was discovered to be radioactive. It was found by Sir William Crookes that uranium could be separated into two constituents, one of which was inactive, and the other, much

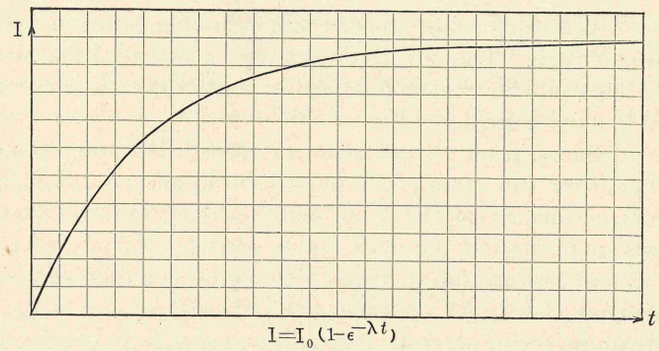
smaller in amount, was relatively intensely radioactive. His method of separation consisted simply in precipitating a solution of uranium nitrate by ammonium carbonate. The greater portion of the precipitate was redissolved by an excess of the reagent, but a residue, consisting chiefly of impurities in the uranium salt, was left undissolved. This residue carried with it the radioactive constituent of the uranium, and was given the name uranium *X*. The redissolved uranium was found to be inactive. But it is important to observe that tests of the radioactive property were made by the photographic and not the electrical method. Now it is the beta and gamma rays which produce, under usual conditions, the whole photographic effect. The alpha rays are so easily absorbed that the covering used to protect the plates from light also shields them from the alpha rays. The activity measured in these experiments may thus be called the beta-ray activity. On allowing the inactive uranium and the active uranium *X* to stand for a time it was found that the former recovered its initial activity after a few months, while the latter in the same time lost its activity. By making quantitative determinations of the radioactivity by the electrical method, using only the beta rays, Rutherford and Soddy determined the law of the decay of activity of the uranium *X* and the rise in activity of the uranium. Let *I* be the activity at any time, and *Io* the initial activity. The law of decay was found to be

$$I = I_0 \epsilon^{-\lambda t}$$



and the law of recovery

$$I = I_0 (1 - \epsilon^{-\lambda t})$$



where λ is a constant. The illustrations herewith show graphically the forms of the curves expressed by these two equations.

Results exactly analogous were obtained with thorium, from which a constituent thorium *X* was separated. In this case the decay of activity of the thorium *X* and the recovery of activity of thorium were much quicker than in the case of uranium. This means that the constant λ has a larger value for thorium than for uranium.

These results led Rutherford and Soddy to the disintegration hypothesis of radioactivity, which we shall now describe.

The old idea of the atom was that of an unchangeable mass, the smallest mass that could be thought of. There were as many different kinds of atoms as chemical elements. Of all the elements hydrogen has the lowest atomic weight and hence the hydrogen atom was supposed to be the smallest mass that could exist. It is true that there had been speculations in regard to the possibility of considering all atoms to be built up of various combinations of one substance, but there was no certain experimental foundation for such speculation and little, if any, progress was made in this direction. It was quite customary to look upon the atoms as hard elastic spheres of the various chemical elements. The study of the spectra of the various elements showed that no such simple view of the atom could be accepted; that the atom must be considered as a dynamical system in order to be capable of giving the very complicated system of spectral lines which most elements exhibit. But spectroscopy has not told us very much about the nature of the dynamical systems which we must take the atoms to be. Up to the time of the discovery of radioactivity, it was supposed that these dynamical systems forming the atoms were all stable systems—

under no conditions could one of them ever change into another of different type. This we may take as the essential feature of the old idea of the chemical atom—its absolute stability considered as a dynamical system.

The disintegration hypothesis discards this requirement of stability for the atom. We must look upon the radioactive elements as formed of the least stable atoms; non-radioactive elements as formed of the most stable atoms. This is certainly not a violent assumption to make, although it is a radical change from former views. If we knew the structure of the atom, all the influences acting upon it, it would be possible to predict just what each atom would do under any conditions. But we do not know this and so we have to make use of probability methods, just as in the kinetic theory of gases we make use of probability methods to find the mean velocity of the molecules.

Let us look upon the atoms as containing alpha and beta particles. We shall have more to say later as to the structure of the atom from this point of view. The atoms being unstable, in a given time a certain number of them will disintegrate, expelling one or more alpha or beta particles, or both. The atom thus changes into an atom of a different kind. Let us assume that the number of atoms which disintegrate in unit time is proportional to the whole number of atoms of its own kind present. If we start with N_0 atoms of a certain kind, the number N after a time t will be given by

$$\frac{dN}{dt} = -\lambda N$$

This expresses that the rate at which the atoms disintegrate is proportional to the whole number present at any time. We can integrate this equation at once, and get

$$N = N_0 \epsilon^{-\lambda t}$$

Thus, it is only after an infinite time has elapsed that all the atoms disintegrate. It will help our understanding of this theory to apply it to a definite case. Let us suppose that all the uranium X has been separated from a given amount of uranium by chemical means. We know that uranium X emits beta particles. Assume then that an atom of uranium X disintegrates into a non-radioactive atom and that the disintegration of each atom is accompanied by the expulsion of one beta particle. The number of beta particles emitted in a

given time will then be equal to the number of atoms which break up in that time, and this is proportional to the number of atoms present. Therefore the beta ray activity I at any time is proportional to N, the number of atoms of uranium X present at that time; we thus have

$$\frac{dI}{dt} = -\lambda I$$

$$I = I_0 \epsilon^{-\lambda t}$$

where I_0 is the initial beta ray activity. This is the law of decay found experimentally by Rutherford and Soddy. Now consider the uranium after the uranium X has been removed. It has no beta activity, but it is continually forming uranium X. Suppose then that an atom of uranium breaks up, expelling an alpha particle, and as a result changes into an atom of uranium X. Its beta ray activity depends upon the number of atoms of uranium X which have been formed. Let N, as before, be the number of atoms of uranium X present at any time t. The number of atoms of uranium is enormous; if the number that disintegrate during a few days is very small compared to the whole number, we can regard the rate of production of atoms of uranium X as constant. Call this q. Then

$$\frac{dN}{dt} = q - \lambda N$$

That is, the atoms of uranium X are produced at a rate q and disintegrate at a rate λN. So the net rate of increase is the difference between these two rates.

The integral of this equation is

$$N = \frac{1}{\lambda}(q - \epsilon^{-\lambda(t+c)})$$

where c is the constant of integration when

$$t = 0 \quad N = 0$$
$$t = \infty \quad N = N_0$$

So that

$$N = N_0(1 - \epsilon^{-\lambda t})$$

Now since the beta ray activity of uranium is due to the uranium

X produced from it, the beta ray activity at a time t after the uranium X has been removed is

$$I = I_0 (1 - \epsilon^{-\lambda t})$$

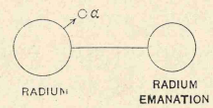
and this is the law Rutherford and Soddy found experimentally for the rise in activity of uranium after removal of uranium X.

After a long enough time has passed, five to six months in this case, the amount of uranium X becomes sensibly constant. In other words, there is radioactive equilibrium between the uranium and uranium X. Just as many atoms of uranium X are produced per second as are destroyed per second. It is not a true equilibrium because we have neglected the number of uranium atoms that disappear in comparison with the whole number. But the uranium atoms disintegrate at so slow a rate compared to the rate of disintegration of the uranium X atoms that the equilibrium between the two appears to be complete.

This hypothesis of the actual breaking down of the chemical atom and the resulting formation of a new atom did not meet with immediate acceptance. Chemists, in particular, were inclined to look upon the production of uranium X from uranium as a case of an ordinary chemical reaction. But this required the assumption that uranium itself was not an element, but a compound which slowly broke up spontaneously into its constituents, just as, under the influence of heat, most chemical compounds break up. But all known chemical reactions are subject to external conditions; temperature and pressure have a marked influence on their rate. The decay of uranium X, on the other hand appears to be absolutely independent of all external conditions. It goes on at the same rate at the temperature of liquid air as at the highest temperatures that may be obtained in an electric furnace. And the same holds true for all other radioactive processes. They appear to be inherent properties of the atoms themselves, and no means have yet been found of retarding or accelerating them.

We have now had two examples of radioactive disintegration—uranium and thorium. Let us now turn to radium and see how the disintegration hypothesis works out in this case. We have seen that radium has all the characteristics of a chemical element—a definite atomic weight, a definite spectrum, and distinct chemical properties so that it may be separated from other elements. Now in studying the radioactive properties of radium it was soon found that there were many irregularities in the

ionization produced by the rays from it. Air currents blowing over the uncovered radium, in particular, had a marked influence on the conductivity of the surrounding air. The ionization was much less from radium that had been freshly evaporated from solution than from the radium after it had stood for some days. Heating the radium produced a temporary diminution in its activity. It seemed as if a gaseous emanation, itself radioactive, was constantly forming in the radium and being occluded in it, so that heat and solution removed the store of this occluded gas. A simple way of studying this supposed gas was found in bubbling air through a solution of radium and collecting this air in a closed vessel. It was found that the conductivity of the air was enormously increased, that its conductivity gradually diminished, falling to half its initial value in about four days, but not according to a simple exponential law. It was found that objects immersed in it became themselves temporarily radioactive, particularly if they were negatively charged. This is the phenomenon known as induced or excited radioactivity. When radium was dissolved in water and air bubbled through the solution there was at first a very large amount of the emanation carried over. After a short time things reached a steady state. This may be explained by the disintegration hypothesis, if we assume that the radium atoms in disintegrating form atoms of emanation. This process goes on continuously and in the solid radium the emanation becomes occluded. In equilibrium there will be just as many atoms of the emanation formed in a second as disintegrate in a second—very little escapes from the solid radium. When the radium is in solution and air is bubbled through, the emanation is removed as fast as it is formed. The first stage in the disintegration of radium may then be represented:



We have spoken of this radium emanation as a gas and we must now examine the evidence for this assumption, and see what kind of a gas it is. If this assumption is correct it should have a definite spectrum, a definite density, and it should be possible to liquify it by increasing the pressure or lowering the temperature, or both. First, as to its spectrum. The emanation from a large quantity of radium was collected, freed from impurities and introduced into a spectrum tube. A wholly new set of

spectral lines, unlike the lines from any known substance, was found. In the course of a few days this spectrum gradually weakened and disappeared, the spectrum of helium finally taking its place. This is of course exactly what we should expect if the emanation disintegrates with the expulsion of alpha particles, for the alpha particles are charged atoms of helium.

Rutherford succeeded in liquifying the emanation at a temperature of -65 deg. cent. at atmospheric pressure. The vapor pressure of the liquid emanation has been determined for a wide range of temperature. Thus, in this respect, it behaves as an ordinary gas.

The determination of the density of the radium emanation was accomplished by Sir William Ramsay. It was a problem requiring extraordinary experimental skill for its solution. The method consisted in actually weighing a known volume of the emanation. When we consider that the weight of the emanation was of the order of $\frac{1}{1000}$ of a milligram it will readily be seen that a very accurate determination was impossible. The density was found to be 111.5 times that of hydrogen, and assuming that the emanation is a monatomic gas, this makes the atomic weight 223. The atomic weight of radium is 226; and if, then, the radium atom emits in disintegrating a single particle, whose weight is 4—the atomic weight of helium—this should leave for the atomic weight of emanation, into which the radium disintegrates, the value 222. This is in surprisingly good agreement with the number found when we remember the extremely small amount of the emanation available.

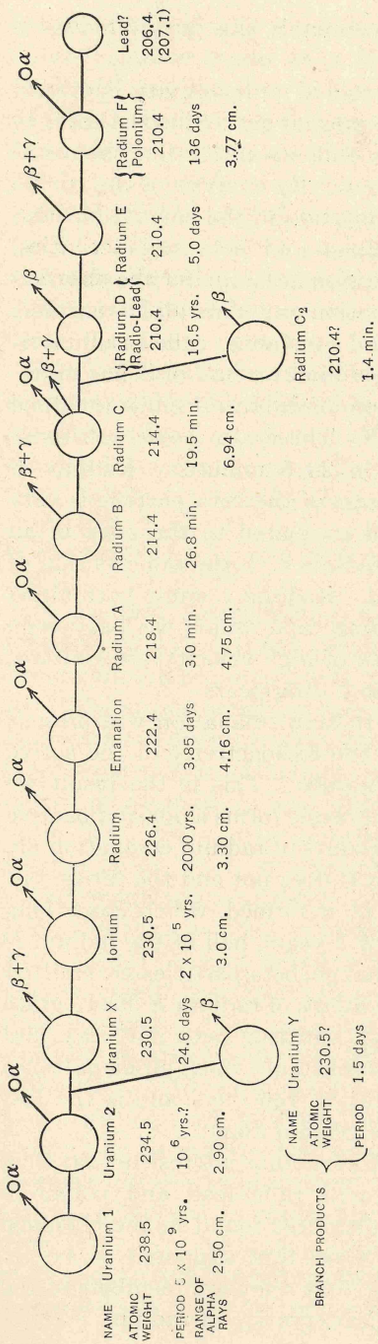
We are thus justified in looking upon the radium emanation as a gaseous element differing in no respect from an ordinary element except that its atoms are far less stable. Let us now see what becomes of the emanation after it disintegrates. We have seen that solids immersed in the emanation become temporarily radioactive. This effect is specially marked if conductors charged to a high negative potential are immersed in the emanation. Everything is exactly the same as if a solid substance were deposited on the metal surface. For example, this active deposit may be dissolved in acids, leaving the metal non-radioactive; while if the solution is evaporated to dryness the residue is found to be radioactive, its radioactivity diminishing in the same way it would have if left on the metal. The active deposit may also

be removed by sandpapering the metal; the dust removed is then radioactive.

When the decay curve of this excited radioactivity is drawn, it is found not to be a simple exponential curve like the curve of decay of uranium *X*. Its form depends upon the time the metal has been immersed in the emanation. By analysis of the curves obtained for different times of immersion in the emanation and by measuring separately the alpha and beta ray activities, it is found that the following succession accounts for the observations. The atom of radium emanation emits an alpha particle, and becomes then an atom of a solid substance, called radium *A*. Radium *A* has a short life; in three minutes half of it has disappeared. In disintegrating, the atom of radium *A* emits an alpha particle and changes into radium *B*. This is also a solid substance disintegrating to half its value in 26.5 minutes. Radium *B* emits only beta particles. The mass of the beta particle is very small so that it can be neglected compared to the mass of an atom; thus the atomic weight of radium *C* is the same as that of radium *B* from which it is formed. Radium *C* emits both alpha and beta particles; and also gamma rays, which we have seen are to be expected when beta rays of high velocity are emitted. In 19.5 minutes half of the radium *C* disappears.

If only a small amount of the radium emanation was present to begin with, after a few hours the radioactivity of the active deposit becomes too small to measure. This is the result we should have if radium *C* on disintegrating forms a non-radioactive substance. If, however, large amounts of radium emanation are employed it is found that radium *C* does not end the series, but that another substance, radium *D*, is formed, which has a long life compared to radium *C*. In 16.5 years, half of the radium *D* changes into radium *E*. In this change, beta particles are emitted by the atoms of radium *D*. The atoms of radium *E* disintegrate to half their number in 5.5 days, emitting beta particles, and forming atoms of radium *F*. This substance emits alpha particles only, decaying to half its amount in 136 days, and is the last member of the series that we are certain about.

Radium *D* and radium *F* are of particular interest in that they have been found to be identical with radio-lead and polonium respectively—two radioactive substances found in the chemical analysis of pitchblende, which were first supposed to be independent substances. We see that they are members of the family which is formed by the disintegration of radium.



You will notice that for the last member of this family I have put down lead, with an interrogation point. The evidence for this is not conclusive, but there is enough to make it seem probable. In the first place, assuming that every time an alpha particle is emitted the weight of the atom is reduced by 4, the atomic weight of helium, the last member of the series should have an atomic weight equal to that of radium, less four times the number of alpha particles emitted in the complete disintegration. Looking at the diagram we see that there are five changes which are accompanied by the emission of an alpha particle. So the atomic weight of the last member of the series should be

$$226.4 - 4 \times 5 = 206.4$$

The element that has an atomic weight nearest this number is lead, whose atomic weight is 207. The discrepancy between these two numbers may possibly be accounted for in this way. There is some evidence that the atoms of radium *C* break down in two different ways. Some of them yield radium *D* and the others yield a substance called radium C_2. On the diagram this is called a branch product. If radium C_2 with a probable atomic weight of 210.4 disintegrates without emitting any alpha rays the final product will have the same atomic weight. As the amount of

radium *C* that forms the branch product is small compared to the amount that forms radium *D*, the mean atomic weight of the two final products would be somewhat greater than 206.4 and might therefore be assumed to be equal to the atomic weight of lead. This view requires us to regard what we call lead as a mixture of atoms of two different kinds, of chemical properties so similar that no way has ever been found of separating them. There is nothing inherently improbable in this view and it is suggested as one way of identifying the final member of the radium family as lead. Indirect evidence that this is so is found in the fact that in many minerals there is a definite relation between the amounts of radium and lead present. This could hardly be explained in any way than that lead is formed from radium.

Let us now examine the other end of the series. It has been well established that in uranium minerals there is a fixed ratio between the radium and uranium present. It is found that for every gram of uranium there is an amount of radium equal to 3.4×10^{-7} grams. A very few minerals show exceptions to this ratio; but these exceptions are satisfactorily accounted for by decompositions or chemical replacements for which there is other evidence. As uranium has the highest atomic weight of all the known elements we naturally take it as the parent element in the whole series.

We saw that the discovery leading to the disintegration hypothesis was that from uranium a substance, uranium *X*, continually produced by the uranium, could be separated by chemical means. There is evidence, however, which there is not time to give here, that uranium does not disintegrate directly into uranium *X*, but into an intermediate substance, uranium 2, the disintegration of each atom being accompanied by the expulsion of an alpha particle. We know of no method by which uranium 1 and uranium 2 can be separated. We may look upon what we call uranium as in reality a mixture of two substances, uranium 1 with atomic weight 238.5 and uranium 2, with atomic weight 234.5; the latter is present in so small a proportion as not to affect the mean atomic weight, which is that of uranium as we know it (238.5). Between uranium *X* and radium there is one member, ionium, discovered by Boltwood. The atoms of ionium disintegrate, with the expulsion of an alpha particle, into atoms of radium.

We must now see how it is possible to determine the rate of decay of the various members of the series. For those that decay

rapidly—say to half their initial value in a few months or less—the rate of decay may be determined by analysing the curves obtained by measuring their radioactivity over a sufficiently long period. But this method obviously cannot be employed for those substances which decay very slowly. The period of radium may be determined in the following way. I showed in the previous lecture how the whole number of alpha particles emitted in a second by a radioactive substance can be counted. If we assume that each radium atom on disintegrating emits a single alpha particle, then the number of atoms of radium that break down in a second is equal to the number of alpha particles emitted by it in a second. The ratio of the number that break down per second to the whole number present is the constant λ in the equation

$$N = N_0 \, \epsilon^{-\lambda t}$$

Now Rutherford has found that the whole number of alpha particles emitted in a second by one gram of radium is 3.4×10^{10}. We now must find the number of atoms of radium in one gram. A cubic centimeter of hydrogen has a mass of 9×10^{-5} grams. If there are n molecules in a cubic centimeter of any gas, there are $2n$ atoms of hydrogen in a cubic centimeter. So that in one gram of hydrogen there are $\frac{2n}{9 \times 10^{-5}}$ atoms. In one gram of radium there will accordingly be

$$\frac{2n}{9 \times 10^{-5} \times 226.4} \text{ atoms}$$

Taking $n = 6.12 \times 10^{19}$ we find the number of atoms in one gram of radium to be

$$3 \times 10^{21}$$

Therefore

$$\lambda = \frac{3.4 \times 10^{10}}{3 \times 10^{21}} = 1.1 \times 10^{-11}$$

Now, remembering that $N = N_0 \, \epsilon^{-\lambda t}$, and putting $N = \frac{1}{2} N_0$ we find

$$\epsilon^{-\lambda T} = \frac{1}{2}$$

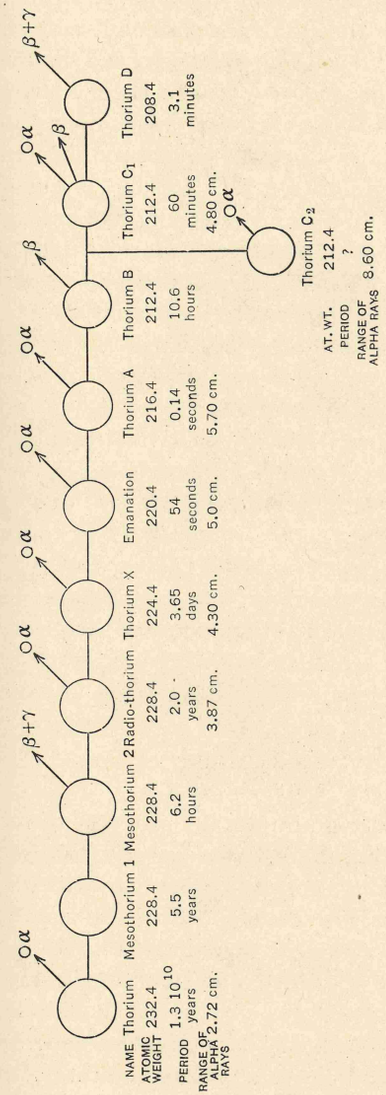
where T is the time for the substances to be half transformed.

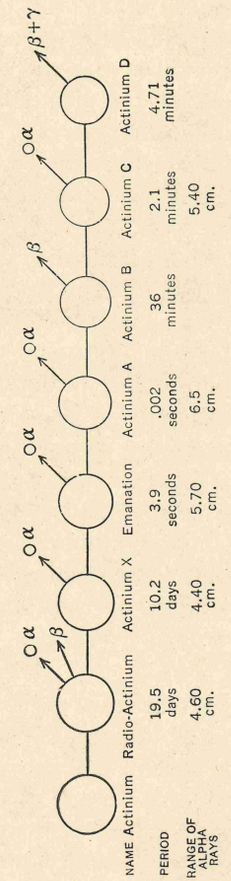
Therefore

$$T = \frac{\log 2}{\lambda} = \frac{0.693}{\lambda}$$

For radium, therefore, $T = 6.3 \times 10^{10}$ seconds or 2000 years.

This same method may be applied to any substances which emit alpha rays that can be counted.





Since the uranium atom emits altogether three alpha particles in changing to radium the atomic weight of the latter should be

$$238.5 - 3 \times 4 = 226.5.$$

This is in excellent agreement with the value found for it by Madame Curie.

In the diagram illustrating the radium series is given, in the last row of figures, the range of the alpha particles emitted by the various members of the series. These numbers give the distance, in air, that the alpha particles traverse before their energy is reduced sufficiently for them to lose their ionizing power. It is seen that with one exception the shortest-lived products emit alpha rays with the highest velocities. This is what one would expect if the disintegration of an atom is anything like an explosion. The shorter the life of an atom, the more violent one would expect the explosion to be, and consequently the alpha particle would be ejected with a higher velocity than if the explosion were less violent. By determining the range of the alpha particles from any product we thus have an independent way of getting an estimate of the life of the product.

There are two other known series of radioactive elements, the thorium series and the actinium series. There is not time to discuss these in detail, but accompanying this are two diagrams similar to the one for the radium series, which give our present knowledge regarding them. There is some evidence that both these series are derived from uranium; the members of both series are found in uranium minerals, which point to their derivation from uranium. It may be that they come from branch products in the main uranium—lead series. But, so far, any direct evidence for this view is lacking.

Heating Effect of Radium

We are now going to consider an important property of radioactive substances—their heating effect. We have seen that radioactive substances are continually sending off particles with a high velocity. Some of these particles are stopped in the substance itself and some in the walls of the containing vessel. As in the case of ordinary projectiles, when brought to rest, the kinetic energy of their motion is changed into heat, so we should expect a radioactive substance to keep itself at a higher temperature than its surroundings. We can easily calculate the rate of heat

production in any radioactive substance as soon as we know the number, mass, and velocity of the particles emitted by it in a given time. For each particle of mass m and velocity v has an amount of kinetic energy equal to $\frac{1}{2}\ m\ v^2$. If n particles are emitted in a second the whole kinetic energy is $\frac{1}{2}\ m\ n\ v^2$, and if all these particles are brought to rest the heat produced in mechanical units is $\frac{1}{2}\ m\ n\ v^2$. To get thermal units, that is, calories per second, we have to divide by the mechanical equivalent of heat, 4.2×10^7. Let us apply this to calculate the amount of heat produced by one gram of radium when it is in radioactive equilibrium with the emanation, radium A, B, and C. This will be the case a week or two after preparation of the radium. The velocities of the alpha particles from the various members of the uranium family are given in the following table.

Product	Velocity of alpha particle	Kinetic energy of alpha particle
	cm. per second	ergs
Uranium 1	1.45×10^9	0.645×10^{-5}
Uranium 2	1.53×10^9	0.72×10^{-5}
Ionium	1.56×10^9	0.746×10^{-5}
Radium	1.61×10^9	0.794×10^{-5}
Emanation	1.73×10^9	0.915×10^{-5}
Radium A	1.82×10^9	1.01×10^{-5}
Radium C	2.06×10^9	1.31×10^{-5}
Radium F	1.68×10^9	0.866×10^{-5}

One gram of radium emits 3.4×10^{10} alpha particles in a second; so the number of particles emitted by one gram of radium with the three products in equilibrium with it is

$$4 \times 3.4 \times 10^{10} = 13.6 \times 10^{10}$$

The average kinetic energy of the alpha particles from these four products is 1.01×10^{-5} ergs. Therefore the kinetic energy which is transformed into heat per gram of radium per second is

$$1.01 \times 10^{-5} \times 13.6 \times 10^{10} = 13.7 \times 10^5$$

In heat units this corresponds to

$$3.26 \times 10^{-2} \text{ calories per second}$$

or to 117 calories per hour.

In this calculation two causes of heat production have been neglected. One is the absorption of the beta rays. Although their velocity is higher than that of the alpha rays, their mass is so much smaller that the kinetic energy of a single beta particle

is only a small fraction of the kinetic energy of a single alpha particle. Then the kinetic energy of the recoil of the atom, resulting from the expulsion of the alpha particle, has been neglected. This may easily be calculated; for the momentum of the atom is equal in magnitude and opposite in sign to the momentum of the particle. The latter is known, as is the mass of the atom, and so the velocity of the atom is

$$mv/M$$

where m is the mass of the alpha particle (4) and M that of the atom after the alpha particle has been expelled; v is the velocity of the alpha particle. The total heating effect resulting from the recoil of the atoms is less than one per cent of the effect we have calculated. As a result, we find that the heating effect of one gram of radium a few days after its preparation is

118 calories per hour.

Now this is something that can be measured, by placing a known mass of radium in a calorimeter and observing the increase in temperature. Measurements of this kind give results very near the calculated value. In particular, one measurement of Rutherford gave as the heating effect of the radium emanation from one gram of radium, 94.5 calories per hour. The value calculated by the same method as that employed for radium is 94 calories per hour. These results therefore confirm the hypothesis that a single alpha particle is emitted from an atom when it disintegrates.

Another confirmation of the disintegration hypothesis is found in the agreement between the calculated and the measured rate of production of helium. Assuming each alpha particle to be an atom of helium, the number of atoms of helium formed in one second in one gram of radium in equilibrium with the emanation, radium A, B, and C, is

$$4 \times 3.4 \times 10^{10} = 13.6 \times 10^{10}$$

In one cubic centimeter of helium at a pressure of 760 mm. of mercury and at 0 deg. cent. there are

$$2.78 \times 10^{19} \text{ atoms}$$

Therefore in one year there should be produced 154 cubic millimeters of helium. Direct experiment, by Sir James Dewar, gave 169 cubic millimeters a year from one gram of radium. When one considers the difficulty of measuring the extremely small volumes

of helium produced from a small amount of radium in a comparatively short time, the agreement between these numbers is surprisingly good.

Radioactivity and the Age of the Earth

The heating effect of radium and the other radioactive substances has an important bearing upon the problem of the age of the earth. You know that there has been a long-standing controversy between physicists and geologists about this problem. There are two principal methods of getting an estimate of the earth's age by physical reasoning. One method is to calculate the time required for the sun to reach its present size by contraction from an infinite sphere, radiating the heat thus produced at the rate determined by measuring the heat received in unit time on unit surface of the earth. The other method is to calculate the time it would take the earth to reach its present temperature, or rather its present rate of increase in temperature (about 1 deg. cent. in 100 feet) downwards from the surface. These methods give as the limiting age of the earth something between twenty and sixty million years. Now this is altogether too short a time to satisfy geologists, who base their reasoning partly on the fossils found in the different geological strata, and partly on the salt content of the oceans, assuming this to have been brought there from the land.

Lord Kelvin was careful to state that his low estimate of the age of the earth depended on no other source of heat energy being found. We now know that there is another source of heat energy, and that is the heating effect of radioactive substances. Nearly all rocks found on and near the surface of the earth are radioactive. The amount of radium contained in the common rocks in different parts of the world varies between wide limits. Some have a radium content as low as 1.2×10^{-13} grams of radium per gram of rock. But on the average, the surface rocks have a radium content of about 2×10^{-12} grams of radium per gram of rock; they also contain about 6×10^{-6} grams of uranium and 1.2×10^{-5} grams of thorium per gram of rock. If it is assumed that these proportions hold throughout the earth, there would result, from the heating effect of radioactive substances alone, more than ten times the amount of heat that is necessary to account for the present temperature gradient of the earth. So it is probable that the interior of the earth contains far less radium than is indicated by the surface. As a result of the discoveries

in radioactivity, physicists will now allow the geologists all the time they require for the earth to have reached its present state.

There is another interesting application of the study of radioactivity to geology. If the amount of helium in a mineral be measured, and it be assumed that all the helium is a result of radioactive disintegration, a minimum estimate of the age of the mineral can be determined. Such estimates lead to times varying from 200 million years to 1600 million years.

There is another subject that should be spoken of in connection with the disintegration hypothesis we have been describing. That is the question of the possibility of reversing any of these radioactive changes, and of bringing about disintegration in atoms which under ordinary circumstances are stable. The disintegrations we have described take place of themselves. External conditions appear to have no effect upon them. It has not been found possible in any way whatever to change the rate at which they take place. For example, radium emanation may be passed through a white-hot platinum tube; it still decays at the same rate. It may be condensed to a solid; the solid emanation decays at the same rate as the gaseous emanation. Now the question is, is it possible to cause the atoms of substances not known to be radioactive to disintegrate? A few years ago Sir William Ramsay announced that he had succeeded in producing lithium in a solution of copper containing a large amount of radium emanation. The reasoning which led him to make such an experiment was this. Radium emanation, in its disintegration, liberates an enormous amount of energy compared to the energy involved in any ordinary chemical change. The amount of energy liberated by one cubic centimeter of radium emanation is about ten million times the amount of energy liberated when a cubic centimeter of hydrogen is burned. And the latter is the chemical change which yields the greatest amount of energy of any ordinary chemical process. If, now, this energy liberated in the disintegration of the emanation can be brought to bear upon the atoms of ordinary elements, there might be a possiblity of breaking them up. A favorable condition for making this experiment is to have the emanation in solution with another substance, and Sir William Ramsay thought that in this way he had succeeded in breaking up copper atoms, with atoms of lithium as one of the products. The experiment has been repeated by others, but no confirmation of it has thus far been obtained. So we cannot say that the possibility of breaking up an atom of non-radioactive matter has been proved.

Many of you have probably seen accounts during the last few weeks of experiments by Collie and Patterson, in England, on the actual building up of chemical elements. Their experiments did not make use of the energy liberated in the disintegration of a radioactive substance, but they employed the energy of an electrical discharge through vacuum tubes. In brief, their experiments consisted in passing electric discharges through vacuum tubes, breaking up the glass, and heating it to drive off any occluded gas. This gas was then examined spectroscopically, and it was found to contain small amounts of helium and neon. They ascribed the presence of these gases to an actual synthesis resulting from the electric current. While it is impossible to say definitely that their conclusion is not true, there are too many other possible ways of accounting for the presence of these gases to give us much confidence in their experiments as proving the synthesis of matter. Inasmuch as the disintegration of a single atom of a radioactive substance involves the liberation of a relatively enormous amount of energy, one would expect that an equivalent amount of energy would be required to build up an atom. So we must feel very sceptical about accepting as true the possibility of the synthesis of matter. The whole problem is a fascinating one, but we cannot say that any certain progress has been made in its solution.

So far, of the previously known elements, only two of them, uranium and thorium, have been found to have marked radioactive properties. It is an interesting question whether the other elements also are radioactive. We should rather expect this to be the case. If we regard the atoms of the various chemical elements as dynamical systems, we should expect them to exhibit various degrees of stability; the elements that we call radioactive are formed of the least stable atoms; and the elements that we call non-radioactive are so only because their atoms are so stable that too few of them disintegrate in a given time to produce radioactive effects. It is known that other properties are shared by all elements in varying degrees. Take, for example, the magnetic property. All elements show a magnetic quality, but it is only a few of them, notably iron, nickel, and cobalt, that have this property to any marked extent.

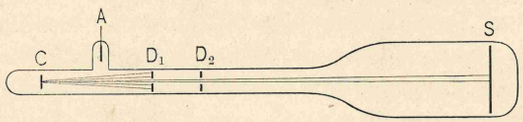
There is a good deal of evidence that the metals rubidium, potassium, and sodium are radioactive, although much less so than uranium and thorium. The wide distribution of radium, found, as it is, in minute quantity in nearly all minerals, gives

rise to the suspicion that the observed radioactivity of ordinary materials may result from the presence of a trace of radium. But in the case of the three metals mentioned, the fact that their observed activity seems to be independent of their source or method of preparation, leads to the view that they are themselves really radioactive substances. And, besides, the rays emitted by them have a character distinct from those emitted by any of the other known radioactive substances. Great care is needed in making experiments to determine the presence of minute traces of radioactivity; for laboratories in which radium emanation has been allowed to escape soon become contaminated by the active deposit that forms on the walls and on all solid objects, so that there is always the possibility of getting spurious effects.

In this lecture I have attempted to show that our old idea of the atoms of the elements as necessarily permanent, must be given up. Instead, we must look upon the atoms of the radioactive elements as unstable dynamical systems. And, probably, the atoms of all elements must be thought of in the same way. Those which appear to be non-radioactive may be thought of as formed of relatively stable atoms, disintegrating at too slow a rate to make it possible, by any means we now know, to detect radioactive effects from them. This view involves no violation of the principle of the conservation of energy. The energy emitted by the radioactive substances in the three kinds of rays is drawn from the internal supply of energy of the atoms.

LECTURE III

The purpose of this lecture was to illustrate by experiment some of the phenomena described in the previous lectures, and to give a little fuller account of some of the subjects touched upon. The first experiments shown had for their object the illustration of the chief characteristics of the cathode rays. By means

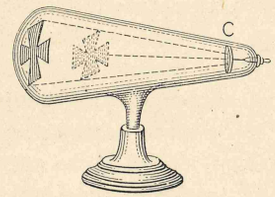


of an induction coil an electric discharge was maintained in a tube of the form illustrated herewith. C is the cathode and A the anode. D_1, D_2 are two diaphragms with small holes which serve to limit the beam of cathode rays, so that they produce a spot of light on the phosphorescent screen, S. By bringing

a magnet near the tube the spot of light was made to move over the phosphorescent screen. The direction in which the spot moved was shown to be what one would expect if the cathode stream is a flow of negatively charged particles, travelling from left to right. For example, when the north pole of the magnet was brought near to, and above the tube, the spot moved forwards; when the north pole of the magnet was brought in front of the tube the spot moved down. In its undeflected position the spot of light was a small circular area. In its deflected position it had broadened out to a band. This was accounted for by the differences in the velocities of the particles. Recalling the expression for the deflection of a charged particle in a magnetic field

$$H\frac{e}{m} = \frac{v}{\rho}.$$

it is seen that the faster moving particles are less deflected than the slow moving particles. As the cathode particles are shot out with all velocities within a certain range, the result is to broaden the spot of light into a band when a magnetic field is applied.



A tube of different form, as in the accompanying illustration, was next shown, which contained an obstacle, in the form of a cross which could be raised or lowered. When it was down, the cathode particles, striking the glass, produced a greenish-yellow phosphorescence. It was the similarity between this light, and the light emitted by certain uranium compounds after exposure to sunlight, that led Becquerel to make the first discovery of radioactive phenomena.

When the cross was raised its shadow was seen as a dark region on the glass, since the obstacle prevented the particles from striking the glass.

Next were shown experiments illustrating the conductivity of air traversed by the rays from radioactive substances. The electric currents passing through the air were measured by the rate of discharge of a parallel plate condenser when a radioactive substance was spread on the lower plate. And this was given by the rate of fall of potential of the insulated plate, when the other plate was charged to a definite potential. The current is given by

$$i = C\frac{dV}{dt}$$

where C is the capacity of the condenser, together with that of the electrometer and the connecting wire. In the experiment this capacity was about 100 in electrostatic units. The electrometer had a sensitiveness such that a potential difference of one volt produced a deflection of about 1000 divisions on the scale. Thus when the electrometer needle moved ten divisions a second, the current flowing through the air was roughly 10^{-12} amperes. It is feasible to measure, by this method, currents as low as 10^{-16} amperes.

Some uranium oxide was spread on the lower plate of the condenser and the motion of the spot of light over the scale determined. Then some of the powdered mineral pitchblende was tested and the spot of light moved about four times as fast, indicating that the radioactivity of pitchblende is about four times that of uranium oxide. A tube of radium, lent by Dr. Kunz, was then placed in the condenser and the spot of light rapidly moved off the scale. In this case the conductivity produced was due to the beta and gamma rays, since the alpha rays were absorbed in the containing tube. With an uncovered radioactive substance it is the alpha rays that produce the greater part of the conductivity.

The conductivity of air containing radium emanation was then shown. For this, a brass cylinder, connected to a 120-volt direct-current circuit, was employed. Insulated from the cylinder, and connected to the electrometer, was a wire inside the cylinder. When radium emanation was introduced into the cylinder, by bubbling air through a solution of radium, and blowing it into the cylinder, a very large increase in the rate of motion of the electrometer needle was seen.

Finally the phenomenon of excited or induced radioactivity was illustrated. A wire, charged to a negative potential, was suspended in a cylinder containing radium emanation, for two or three minutes, and then taken out, and its activity measured in the condenser used in the first experiments on radioactivity. It was found that the wire had a definite activity to begin with, and observations a few minutes apart showed that its radioactivity gradually decayed.

There are some points in connection with the previous lectures about which more should be said. We have seen that a wire placed in radium emanation becomes radioactive itself, and this was explained as caused by the deposition on the wire of solid particles of radium A resulting from the expulsion of an

alpha particle from the atom of radium emanation. As the alpha particle is positively charged, we should expect the atoms of radium A to be negatively charged, and therefore to tend to concentrate on positively charged surfaces. Exactly the opposite is found to be the case. More of the active deposit forms on a negatively charged surface than on a positively charged surface, other conditions being the same. This difficulty has been cleared up by the discovery of what are called "delta" rays. These are negatively charged particles, which travel at too low a velocity to produce any ionizing effects, and which always accompany the emission of alpha particles. They were found in this way. Suppose a radioactive substance, like polonium, which emits alpha rays, but no beta rays, is placed opposite a metal plate, in a very high vacuum, so that the alpha particles will strike the metal plate without, on the way, hitting any air molecules to ionize. We should expect the metal plate to receive a positive charge—the product of the charge of the alpha particle by the number of particles that strike it. It is found, however, when the experiment is made, that the metal plate does not get positively charged. However, by applying a weak magnetic field in a direction parallel to the plate, the latter receives a positive charge. This is exactly the effect that would be produced if, with the positively charged alpha particles, negative particles are emitted. These delta rays travel with so low a velocity as not to produce any appreciable ionization; they are of the same nature as the beta particles except that their velocity is so small that they are very readily deflected by a magnetic field. If, then, when an atom of radium emanation disintegrates, with the expulsion of an alpha particle, it also expels a sufficient number of delta particles, the atom of radium A will be positively charged, and will therefore travel to the negative electrode.

The law of decay that has been found experimentally for a single radioactive substance,

$$I = I_0 \epsilon^{-\lambda t}$$

we have seen, can be deduced from the assumption that the number of atoms that disintegrate in a second is proportional to the whole number present. This may be looked at from another point of view. We may regard each of the atoms of a radioactive substance as equally likely to disintegrate. Not knowing the circumstances that cause an atom to disintegrate, and not being able to follow each atom throughout its whole life, we have to make use of the method of the calculus of proba-

bilities in its simplest form. The calculus of probabilities is, perhaps, the most powerful mathematical method we have for dealing with problems involving atoms or molecules. Its justification lies in its success in accounting for many phenomena. The atoms all being equally likely to disintegrate, the number that do so will be proportional to the whole number. We might look upon the atoms as kernels of corn; the disintegration of an atom as the popping of a kernel. The illustration is not perfect, because as the corn gets hotter the rate of popping increases. But there is a stage which lasts for some minutes, at which the popping occurs fairly regularly. Now it is obvious that with only a few kernels to begin with, there would be no regularity in the popping. One kernel would pop, then several seconds might elapse and a number of them would pop almost simultaneously, and then there might be a fairly long interval before another one popped. But with a very large number of kernels to begin with, the irregularities are smoothed out. In the steady state referred to, as many kernels pop in one second as in the succeeding one. Thus with a very large number of kernels, probability becomes certainty. So it is in the familiar illustration of chance as applied to drawing a certain card from a pack. The probability of drawing a certain card at one trial is the ratio 1/52. But every one knows that it rarely happens that out of 52 trials the given card is drawn once and only once. It may not be drawn at all, or it may be drawn many times. If, however, there be a very large number of observers, each with a pack of cards, all drawing together, the likelihood that one out of every 52 will draw the given card becomes very much increased; so that with an enormous number of observers, this probability becomes a certainty.

The method, described in the first lecture, of counting the number of alpha particles emitted by a radioactive substance, furnishes a good illustration of this point. If the opening, through which the particles enter the ionization chamber, is made very small, then the ratio of the whole number that enter to the whole number emitted, is very small. The result is that the particles do not enter at equal time intervals. One particle enters, some seconds may elapse, and then two or more particles may enter almost simultaneously. So, to get definite results observations must be taken during a long time; the longer the time during which observations are made, the more accurate are the results in giving the rate at which the particles enter.

Now even in what we call infinitesimal amounts of matter there are enormous numbers of atoms. Therefore the probability that a certain fraction of them will disintegrate in a given time becomes a certainty that they will do so.

The particular fraction is the quantity λ which is characteristic of each substance. For a substance which is not at all radioactive λ is zero. The greater λ the more radioactive the substance. We have seen that the time required for a substance to disintegrate to one-half its initial value is related to λ by the equation

$$T = \frac{0.693}{\lambda}$$

Another interpretation of this important quantity is that its reciprocal tells us the average life of an atom. For if we start with N_0 atoms, the number at any time, t, will be

$$N = N_0 \epsilon^{-\lambda t}$$

The average life of an atom is therefore

$$\frac{1}{N_0} \int_0^\infty N_0 \epsilon^{-\lambda t} dt = \frac{1}{\lambda}$$

The meaning of "radioactive equilibrium" may require a little more explanation. Let us consider what is meant by saying that in a mineral containing uranium, equilibrium exists between the uranium and all its products. By referring to the chart which gives a representation of the whole known series of disintegrations, we see that uranium has a far longer life than any of its radioactive products. If we began with uranium and could remove all of its products from it, the latter would begin to form at once, and after a long enough time had elapsed as many atoms of one of the products would form, in a given time, as disintegrated in the same time. Uranium would then be in equilibrium with its products. Since the uranium itself is breaking down, and, so far as we know, is not being continually formed from any element of higher atomic weight, the uranium itself would not be in equilibrium.

If there are two successive products, 1 and 2, so that 2 is

formed by the disintegration of 1, the rate of increase of atoms of 2 will be given by

$$\frac{dN_2}{dt} = \lambda_1 N_1 - \lambda_2 N_2$$

for $\lambda_1 N_1$ is the number of atoms of 1 that break down a second; that is, the rate of formation of atoms of 2; $\lambda_2 N_2$ is the rate of disintegration of atoms of 2. So the difference gives the net rate of increase of 2. If there is radioactive equilibrium between 1 and 2, $dN_2/dt = 0$; that is, the number of atoms of 2 that form from 1 per second must be equal to the number of atoms of 2 that disappear per second. So that

$$\lambda_1 N_1 = \lambda_2 N_2$$

or

$$N_2 = \frac{\lambda_1}{\lambda_2} N_1$$

If A_1 and A_2 are the atomic weights of the two products, the mass of 1, M_1, in equilibrium with a mass M_2 of 2 will be

$$M_2 = \frac{\lambda_1}{\lambda_2} \frac{A_2}{A_1} M_1$$

or if T_1 and T_2 are the times for 1 and 2 to be half transformed, we can write this

$$M_2 = \frac{T_2}{T_1} \frac{A_2}{A_1} M_1$$

By the use of this equation we can find the amount of any product in equilibrium with its parent. Suppose we have a mineral containing one gram of radium. The amounts of the various products in equilibrium with this will then be given by the successive applications of this equation. In this way we can calculate the following table:

Name	A	T	M grams
Radium	226.4	2000 yr.	1
Emanation	222.4	3.85 days	$5.2\ 10^{-6}$
Radium A	218.4	3 min.	$2.8\ 10^{-9}$
Radium B	214.4	26.8 min.	$2.4\ 10^{-8}$
Radium C	214.4	19.5 min.	$1.8\ 10^{-8}$
Radium D	210.4	16.5 yr.	$7.9\ 10^{-3}$
Radium E	210.4	5 days	$6.5\ 10^{-6}$
Radium F	210.4	136 days	$1.8\ 10^{-4}$

We see that in a mineral containing one gram of radium we must expect to find 1.8×10^{-4} grams of polonium (radium F). The amount of the latter which can be obtained is therefore extremely small.

It is found that in a mineral containing one gram of uranium there is an amount of radium equal to 3.4×10^{-7} grams. So, in order to find the amount of any of the products of radium in equilibrium with one gram of uranium, we need only multiply the numbers in the last column of the above table by 3.4×10^{-7}.

We must believe that each member of the uranium series, and also each member of the thorium and actinium series, is a definite chemical element, with definite chemical properties and a definite spectrum. The reason why the properties of so few of these elements are known is now seen to be the result of the very minute amounts of them that are available. In the uranium series, we have fairly complete knowledge of the chemical properties and the spectra of uranium, radium, and the emanation. There is some evidence, also, of a definite spectrum belonging to radium F (polonium). Many of the chemical properties of the other members of this series are known, but this knowledge is by no means complete.

A great deal of interest has been aroused in the medical applications of radium. So far as we know, there is no other practical use for it. The rays emitted by radium produce burns which are similar to those produced by ultra-violet light and the Röntgen rays, and it is to be expected that they should possess a therapeutic value. I am not able to speak with any authority on this subject, but it is a fact that a good deal of work is being done—particularly in England and on the continent—along these lines, and announcements of success in the application of radium and the radium emanation are frequently made. Progress in this direction is retarded by the small amount of radium which is available. The principal source of radium is the mineral pitchblende, and the chief known deposits of this mineral are owned by the Austrian government, which also controls the manufacture of radium from it.

In conclusion I am going to give an approximate calculation of the amount of energy set free when one gram of uranium is transformed into the last member of the series, which we may take to be lead. In this transformation eight alpha particles are emitted, with an average velocity of

$$v = 1.68 \times 10^9 \text{ cm. per second}$$

The mass of an alpha particle is four times the mass of an atom of hydrogen, or $m = 4 \times 1.7 \times 10^{-24}$.

Thus the average kinetic energy of the alpha particles emitted by uranium is $\frac{1}{2} m v^2$, or

$$9.6 \times 10^{-6} \text{ ergs}$$

and the kinetic energy of the eight alpha particles is therefore

$$7.7 \times 10^{-5} \text{ ergs.}$$

This is the energy set free when one atom of uranium breaks down into lead. In one gram of uranium there are

$$\frac{1}{238.5 \times 1.7 \times 10^{-24}} = 2.5 \times 10^{21} \text{ atoms.}$$

Therefore the energy set free when one gram of uranium turns to lead is $7.7 \times 10^{-5} \times 2.5 \times 10^{21} = 1.9 \times 10^{17}$ ergs.

Now suppose it were possible enormously to increase the rate at which this change takes place. Instead of millions of years, suppose it took place in one second. The rate at which work would be done is then

$$\frac{1.9 \times 10^{17}}{7.46 \times 10^{9}} = 2.5 \times 10^{7} \text{ horse-power.}$$

Uranium thus has an enormous store of energy contained in its atoms. We must believe that all the elements contain equivalent amounts of energy in their atoms. But no means is known of drawing upon this supply of energy, nor even of hastening its liberation from those elements which do disintegrate spontaneously.

It is the province of science to discover the laws of nature; the province of engineering is to apply them. And therefore we must leave to the engineers the problem of making use of this enormous store of energy concealed in the atoms of all matter.

LECTURE IV

I am going to speak of a discovery connected with radioactivity which is of very far reaching importance. It has to do with the dependence of the mass of a corpuscle, or electron, upon its velocity. The bare statement of this discovery is startling when viewed from the standpoint of our customary ideas about matter. We are accustomed to look upon mass as an unalterable attribute of matter. Newton's laws of motion—which are the foundation upon which the science of mechanics rests—are based upon the idea of the constancy of mass.

The conception we have formed up to this point of a corpuscle —or an electron—is that it is a particle of matter charged with electricity. This conception involves two unknown quantities—matter and electricity. We all think we know what matter is. We are so familar with matter in its various forms that we are inclined to think it needs no explanation. Of electricity, on the other hand, we think we know less. Familiarity with electric phenomena comes into our lives much later than familiarity with matter, so that we feel that electricity is a mystery compared to matter. It is worth considering very briefly whether this is so or not—whether matter is really a simpler conception than electricity. According to chemists we have to assume some eighty or ninety different kinds of matter—the different chemical elements —so that matter is not a simple conception, by any means. But more than this, for a material view of the universe we have to assume the existence of another kind of matter which differs in its properties from any kind of matter that we are familiar with—the ether. It is true that Lord Kelvin's model for an ether formed of interlocking cog-wheels does help us in realizing the possibility of the existence of a substance with the apparently contradictory properties that the ether must have to fulfill its requirements. And, from another point of view, the attempt has been made to conceive of the atoms of the various chemical elements as built up of the ether. The best known of these hypotheses is the vortex-atom hypothesis of Lord Kelvin. Assuming the ether to be a perfect fluid, a vortex ring formed in it would have the one essential quality we had always believed the atoms to have, absolute permanency. But, with the discoveries in radioactivity, that is no longer an essential, as we have seen. The difficulties in the mathematical analysis involved in working out to its conclusion this hypothesis are too great for our present methods, and so it has remained merely a suggestion. As for

the problem of interpreting electricity in terms of matter, that, too, has remained unsolved. We may speak of an electric charge as a singular point in the ether—a center of strain—but that is not an easy conception to form. And then again we have the baffling problem of gravitation. We know no more today why the apple falls than Newton did.

What I wish to emphasize in all this is that the attempt to reduce the physical universe to its lowest terms in the form of matter has not been very successful, and while I believe that much more progress can and will be made in this direction, for the present we seem to have reached a point at which we do not know where to turn to make this progress.

Suppose, then, that of our two unknown quantities in the conception of an electron, matter and electricity, we try to explain matter in terms of electricity. For this purpose electricity is a conception that we do not need to explain. It is our fundamental conception from which we are going to attempt to derive matter and the physical universe in general. It is difficult to make myself clear on this subject—mainly because it is not easy for me to conceive of electricity not associated with matter. It is hard to form a conception of anything being more fundamental than matter. But for the purpose of building up a logical scheme for the universe we must try not to let our inherent prejudices blind us to accepting another possibility. And by continual thinking along these lines the time may come when electricity will seem just as simple a conception to us as matter does now.

The goal towards which science aims is the reduction of the physical universe, and all the processes going on in it, to the lowest terms, and for this object it makes no difference whether we take electricity or matter as fundamental. If we find that we can get a consistent scheme for interpreting all the universe in terms of electricity, then electricity will be the fundamental conception —and when that is done it will be time enough to see whether we can go back of our conception of electricity. I do not wish to be understood as promising to exhibit to you any such complete scheme, but I shall try to make clear to you the trend of a large part of modern physics.

The smallest electric charge that has ever been determined is the charge on an electron—or corpuscle. And the smallest mass that has ever been determined is the mass of an electron or corpuscle. Our first question, then, is, can we interpret the mass of a corpuscle in terms of its electric charge?

Suppose, then, that we have what we may call a particle of electricity. Two such particles will repel each other with a force inversely as the square of the distance between them. We cannot make the experiment of measuring the force between two particles of electricity—we can only measure the force between two bits of matter that are charged with electricity. But we first of all make the hypothesis that the force which we can measure is a force between the electric charges. Now merely to say that there is a force between two particles of electricity does not satisfy us. Our minds are so constituted that we must form a picture of something which will transmit this force. We cannot, to be consistent with the view we are now considering, assume a material medium—an ether—pervading all space. For that is equivalent to assuming a kind of matter as a fundamental conception—and we are going to try to get rid of that idea. So we must imagine another way of forming a mental image of the action between the two particles of electricity. Let us, therefore, follow Faraday in assuming that every particle of electricity carries with it lines of force. What these lines of force are we cannot say any more than we can say what electricity is. They are to be for our theory just as fundamental a conception as electricity itself; they are a part of the electric charge. It was proved by Maxwell that all the forces between charged bodies can be interpreted as resulting from a tension along the lines of force and a repulsion perpendicular to them. We shall therefore assume that the lines of force carried by every particle of electricity have this property—of being in a state of tension, like so many stretched elastic bands—and also of repelling each other sideways.

Let us now consider a corpuscle in motion along a straight line. We first suppose that the velocity of the corpuscle is small compared to the velocity of light. Under this condition the lines of force will end on the corpuscle uniformly in all directions. As we cannot suppose that a finite number of lines of force end in a mere mathematical point we shall suppose the corpuscle to be a sphere of radius a, with the lines of force along the radii of the sphere. This leads to a very serious difficulty. If we regard a corpuscle as a very small, but finite, volume of electricity, what is it that keeps it together? If we apply what we know to be the force between two charged particles of matter to the elements into which the finite volume of a corpuscle may be divided, these elements will repel each other, and the corpuscle will fly apart. But since all we really know anything of is the force between

particles of matter containing very many corpuscles, we are not necessarily obliged to assume the same law of force between the elements of a corpuscle. An electric charge in motion is an electric current. An electric current produces a magnetic force, and by Ampere's law the strength of the magnetic force is at any point equal to

$$H = \frac{e\,v \sin\theta}{r^2}$$

where e = charge, v its velocity, r the line from the instantaneous position of the charge to the point at which the magnetic force is required, θ the angle between r and v. Now it is known that the whole amount of work we have to do in order to set up a magnetic field is

$$W = \frac{1}{8\pi}\int\int\int H^2\,dx\,dy\,dz$$

As we suppose the corpuscle to be moving with a velocity small compared to that of light, everything will be symmetrical about it, and we may write this expression

$$W = \frac{e^2v^2}{8\pi}\int_0^{2\pi} d\varphi \int_0^{\pi} \sin^3\theta\,d\theta \int_a^{\infty} \frac{dr}{r^2} = \frac{e^2v^2}{3\,a}$$

In terms of mass, the amount of work we would have to do to get a particle of mass, m, moving with velocity v, is

$$W = \frac{1}{2}\,m\,v^2$$

Thus we must put

$$\frac{1}{2}\,m\,v^2 = \frac{1}{3}\frac{e^2}{a}\,v^2$$

$$m = \frac{2}{3}\frac{e^2}{a}$$

We have therefore interpreted the mass of a corpuscle in terms of its electric charge.

It should be said that there are other expressions for the mass of a corpuscle in terms of its charge which differ from the one we have obtained. The difference arises from the conception we form of a corpuscle. But they are all of this same form—proportional to the square of the charge and inversely proportional to a length, which we may call the radius of the corpuscle.

The expression we have just obtained holds only when the velocity of the corpuscle is small compared to the velocity of light. When the velocity is comparable to that of light the lines of force are no longer symmetrical with respect to the corpuscle and so our simple method of calculating the energy of the motion can no longer be applied. I fear you will not care to follow me through the rather involved mathematics that is required to work out the case of a corpuscle travelling with high velocity. There are in fact several different theories arising from different conceptions of a corpuscle. But all theories agree in showing that what we have defined as the mass of a corpuscle increases very rapidly with its velocity, and approaches infinity when the corpuscle has a velocity equal to that of light. In other words, it would require an infinite force to get a corpuscle moving with the velocity of light.

It is here that we must appeal to experiment to test the validity of these views. We have seen how it is possible to measure the ratio e/m for the corpuscles, and v, their velocity, by deflecting them from their straight line paths in magnetic and electric fields. Radium emits corpuscles—the beta rays—and there is a wide range in their velocity of emission. Experiments to show a connection between e/m and v for the beta particles from radium were first made by Kauffmann. The experiments have been repeated by others, using also the cathode particles in vacuum tubes. All these experiments show that the ratio e/m decreases with increasing velocity of the particles. For example, Kauffmann found that for a corpuscle travelling with a velocity 2.83×10^{10} cm. per second the value of e/m was 0.62×10^7, while for a corpuscle having the smaller velocity 2.36×10^{10} cm. per second, $e/m = 1.31 \times 10^7$. In other words e/m was more than halved for an increase in velocity of only 20 per cent. Now on the view that electricity is our fundamental conception we must suppose that e, the charge of the corpuscle, remains constant, so that the decrease of e/m with increasing velocity means an increase of the mass of the corpuscle as its velocity increases. This is what theory demands, but the experimental results that have

so far been obtained are not certain enough to enable us to decide absolutely in favor of any one of the various theories that have been developed to account for these effects. But we can say that it appears probable that the mass of a corpuscle or electron can be interpreted as resulting from the motion of an electric charge.

Before leaving this subject something should be said about another possible explanation of the increase in mass of a corpuscle with its velocity. That is a proved experimental result, unless we are willing to suppose that the electric charge diminishes with increasing velocity. What is measured is the ratio e/m; this is found to diminish with increasing velocity, so that either the mass increases or the charge decreases. Well, now, in no view of matter—whether we take matter or electricity as a fundamental conception—is there anything else that would lead us to a possible connection between an electric charge and its velocity. We have seen that there is such a connection between mass and velocity in the view we have described, and there is also a connection between mass and velocity in our older view of regarding matter as the fundamental conception. This connection can be illustrated by a very simple analogy. Suppose we have a solid sphere whose mass is m, moving in a fluid. The fluid is supposed to be perfect, so that there is no loss of energy in friction. The work we would have to do to get the sphere moving with velocity v is $1/2\ m\ v^2$ if there were no fluid. But the sphere sets the fluid in motion, pushing it out in front. The calculation of the energy of this fluid motion is one of the simple problems of hydrodynamics; the result is that the energy of the fluid motion is $\frac{1}{2} m_1 v^2$, where m_1 is the mass of a volume of fluid equal to one-half the volume of the sphere. Everything will then be just the same as if the fluid were annihilated and the mass of the sphere increased to $m + m_1$. At rest the sphere has a mass m; its mass is effectively increased by m_1 when it moves through the fluid. Now according to this, the sphere has one definite mass when it is at rest, another definite mass when in motion and this is the same for all velocities. There is no variation of its mass as the velocity increases. If we suppose that the sphere is not a rigid but an elastic body, such a variation will be found. At rest, the fluid pressure on the sphere is equal in all directions—so that the sphere will not be deformed. In motion, the fluid pressure is unequally distributed over the sphere and it becomes flattened in the direction of motion. The work that has to be done to produce the motion of the fluid may still be written in the form $1/2\ m_1\ v^2$, but m_1 increases with the

velocity—that is, the flatter the sphere gets the greater is its effective mass. On this view, then, we get the result that the mass of the sphere is effectively different for different velocities of motion—increasing with the velocity. If, then, we regard the ether as a perfect fluid, and the electron as a particle of elastic matter, we would get just the effect we wish to explain—that the mass of the electron would increase with its velocity.

This view requires the hypothesis of an ether with all of its apparently contradictory properties. But I have tried to show that as far as explaining the increase in mass with velocity we are not absolutely forced to change our inherent feeling that matter, after all, is the fundamental concept. It may be possible to develop these ideas into a consistent scheme which will be more satisfactory than a scheme which builds matter out of electricity.

Whatever view we take of the electron—whether we assume it to be a particle of matter charged with electricity, or a particle of electricity which is endowed with mass in virtue of its motion—we are forced to the conclusion that electrons have a leading part in the constitution of matter as we know it. So far as we have gone we have found electrons only in vacuum tubes when an electric discharge is passed through, and emitted by radioactive substances. But we must suppose them to have a very wide distribution. For example, when a metal surface is exposed to ultraviolet light, corpuscles are emitted that have all the properties of the electrons that we have studied. So also when metals are raised to high temperatures, electrons are emitted, to such an extent that large electric currents can be sent through the highest obtainable vacuum; the current is carried by the corpuscles shot out from a glowing metal. All these effects point to the existence of these electrons in all forms of matter. From whatever source they come, no differences have ever been found among the electrons, except a difference in velocity, which carries with it a difference in mass. Measurements of the ratio e/m for electrons from different sources, and by varying methods for velocities that are small compared to the velocity of light, do not differ from each other by more than can be accounted for in experimental errors and uncertainties.

We are thus led to the electron theory of matter which assumes that the atoms of the various chemical elements are built up, in part, of electrons. The atoms of the different elements will then differ from each other in the number and arrangement of

the electrons they contain. We shall have more to say about this view of the constitution of the atom, but for the present I am going to speak of some of the consequences of such a view, first of all in relation to light.

The view that electrically charged particles play a part in light phenomena is not a new one. It had been suggested, and some of its consequences worked out, long before the discoveries that led to our knowledge of the actual existence of electrons. Now that the existence of the electron or corpuscle has been made certain, its charge and mass determined, we can use the electrons in optical theory with much more confidence than before. We know that the various chemical elements are characterized by having definite spectra. That is, the atom of any chemical element may be supposed, when it is made, by whatever means, to emit light, to emit light of only certain definite frequencies of vibration. The conception of an atom as an elastic solid, and of the frequencies of the light emitted by it as the frequencies of the free vibrations of an elastic solid, has never led to results at all satisfactory in giving vibrations of the frequencies that we have to account for. Let us see what an electron view of the atom will lead to. All the electrons have the same electric charge, and according to our conventions we call the charge negative. Calling it negative is of course of no significance; it is all a matter of the convention that when a piece of glass is rubbed with silk the glass is called positively, and the silk negatively, charged. And it is found that the electron has a charge of the same nature as the charge on the silk after being rubbed on the glass. Now the idea of an atom formed of negatively charged particles will not work. For the negative electrons are going to repel each other and so we have got to imagine something to hold them together to form an atom. We are thus bound to introduce another fundamental conception along with our fundamental conception of electricity, which, we see, corresponds to negative electricity. This new conception is positive electricity. An element of positive electricity we know nothing of, in the sense that we have a knowledge of an element of negative electricity—the electron. At one time it was thought that the alpha particle might be considered as such. We know that the alpha particle carries a positive charge; but now we know that it is a charged atom of helium and so has a structure comparable in complexity with other atoms, that is, is built up, at least in part, of electrons, so that the alpha particle cannot be regarded as a fundamental unit of

positive electricity. We are therefore forced to assume some special form for the positive electricity and examine the consequences of our assumption.

Let us therefore take positive electricity distributed uniformly throughout a sphere whose size is comparable with the size of an atom; *i.e.* having a radius of the order of 10^{-8} cm. The simplest model for an atom will then be this sphere of positive electricity with a single electron inside it. In order that the atom may be neutral, we must assume the whole positive charge equal to the negative charge. If we call a the radius of the sphere and r the distance of the electron at any instant from its center, the force drawing the electron towards the center is equal to

$$\frac{e^2\, r}{a^3}$$

Now the motion of a particle in a circle about a center of force varying directly as the distance is known to be stable, and the time required for the electron to go round the circle once can easily be found.

The equation of motion of the electron is

$$\frac{d^2r}{dt^2} = -\frac{e^2\, r}{m\, a^3}$$

This is the same equation that we have for the small vibrations of a simple pendulum. The time of complete vibration is therefore

$$T = 2\,\pi\,\sqrt{\frac{m\, a^3}{e^2}}$$

Now we have taken

$$a = 10^{-8}$$

we know that

$$\frac{e}{m} = 1.8 \times 10^{7} \text{ in electromagnetic units, or}$$

$$5.4 \times 10^{17} \text{ in electrostatic units}$$

$$e = 4.7 \times 10^{-10}$$

so that

$$T = 4 \times 10^{-16} \text{ seconds}$$

$$\text{wave length} = T \times 3 \times 10^{10} = 1.2 \times 10^{-5} \text{ cm.}$$

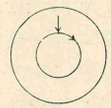
This is of the order of magnitude of the wave lengths we are familiar with in ordinary light. An electron circulating about inside a sphere of positive electricity would thus give rise to electromagnetic waves of the nature of light waves. It must not be thought that this model for an atom is anything more than a mere suggestion; for one thing, the energy of the electron would be radiated away in the form of light energy altogether too rapidly to allow us to consider this an actual atom. And such an atom would have but one frequency of vibration—only one spectral line—but it is certainly of interest that by such a simple mechanism we can get a wave length of light which is comparable to those that we know are present in ordinary light.

The Zeeman Effect

Of all the applications of the electron hypothesis to optical effects, the most striking success has been in explaining the so-called Zeeman effect. Suppose we have, as a source of light, an incandescent gas, and examine the light through a spectroscope. A number of bright lines are seen, forming the spectrum of the particular gas employed. Now let the incandescent gas be placed in a magnetic field by placing the tube containing it between the poles of a magnet. It is found that, in general, the spectral lines are split up—where there was a single line with no magnetic force acting, on exciting the magnet this line has split up into a number of others. Spectroscopes of very high resolving power have to be used in order to make the distance between the lines appreciable. Some spectral lines split up in a very simple way—either into three lines or two lines, depending upon whether the direction of the magnetic force is perpendicular or parallel to the line of sight. Our simple model of an atom serves admirably to explain this phenomenon. To see how this is let us suppose that we have an electron describing a circular path about the center of an atom. Let it make n revolutions per second. On our simple view of an atom of positive electricity containing a single electron we have seen that

$$n = \frac{1}{T} = 2.5 \times 10^{-17}$$

Now suppose a magnetic force acts on the atom. The electron in motion acts as a current element and therefore the magnetic force H exerts a force on the moving electron which is perpendicular to both the direction of the magnetic force and the direction of motion of the electron. In the accompanying illustration let the outer circle represent the section of the atom, and the inner circle the path of the electron, the arrow showing the direction of its motion. Suppose the magnetic force is directed up from the plane of the paper. Then there will be a force, acting on the electron, tending to drive it towards the center of the atom. This force is $e\,v\,H$, while the force drawing the electron to the center resulting from the uniform positive charge of the atom is $\frac{e^2 r}{a^3}$.



Together, these must give the centrifugal force $\frac{m\,v^2}{r}$. Hence

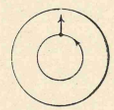
$$\frac{e^2 r}{a^3} + e\,v\,H = \frac{m\,v^2}{r}$$

But $v = n_1\,2\,\pi\,r$, where n_1 is the number of vibrations in one second under the influence of the magnetic field.

Hence

$$\frac{e^2}{a^3} + 2\,\pi\,e\,H\,n_1 = 4\,\pi^2\,m\,n_1^2$$

For an electron moving in the opposite direction, as illustrated herewith, we get in a similar manner



$$\frac{e^2}{a^3} - 2\,\pi\,e\,H\,n_2 = 4\,\pi^2\,m\,n_2^2$$

Subtracting these two equations, we get

$$n_1 - n_2 = \frac{e\,H}{2\,\pi\,m}$$

The difference in the number of vibrations per second for the two extreme lines into which the single line is split in the magnetic field is thus

$$\frac{e\,H}{2\,\pi\,m}$$

and this may be measured optically. Knowing H, the strength of the magnetic field, the ratio e/m may be found. And the value for this ratio that is obtained in this way, using a number of

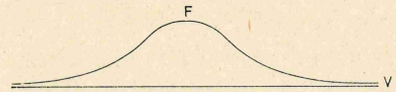
different sources of light, and a number of different spectral lines, is so nearly the same as the value of e/m determined by measurements on cathode particles in vacuum tubes, beta rays from radioactive substances, the corpuscles emitted by metals when exposed to light, or when heated, that we must conclude that light emission is produced by charged particles of the same kind. It is impossible to over-estimate the importance of this result. It furnishes the clearest evidence of the universal existence of the electron and the important part it plays in physical phenomena.

There are more complicated types of the Zeeman effect, where a single line is split up into more than two or three components, and while these cases cannot now be explained satisfactorily, there can be no doubt that the true explanation will be found to depend upon the disturbance in the motion of electrons produced by a magnetic field.

In the theory of light that regards light as the transverse vibrations of an elastic solid ether, and also in the electromagnetic theory of light, there has been a difficulty in accounting for dispersion. Waves of different frequencies travel in material substances with different velocities. The hypothesis was made by Sellmeyer, and developed by many others, including Helmholtz and Lord Kelvin, that there were particles inside matter capable of executing definite vibrations, and that their vibrations so modified the propagation of light through the bodies as to produce the effect of dispersion. These hypothetical particles now have a definite reality. They are the corpuscles or electrons of which we have been speaking. I do not wish to be understood as implying that we are even near a complete theory of the propagation of light through matter, but the fundamental importance of the electron in optical theory is established beyond doubt.

I now wish to consider a point in the general theory of radiation about which we are still very much in the dark. It has to do with the emission of light—or any form of radiant energy—by bodies, when their temperature is raised. The discussion of this question is much facilitated by the introduction of the conception of a " black body." By that is meant a body which absorbs all the radiation falling upon it and reflects none. While an sbaolutely black body is not known, it is easy to get so close an approximation to one, that an ideal black body is not a difficult thing to imagine. When a black body is raised to a definite

temperature it radiates energy from the shortest known light-waves to the longest known heat waves. The intensity of the radiation, arising from any small range of frequencies, can be measured, and when this is done a curve something like the illustration is obtained; ν is the frequency, the number of vibrations of the radiation in 2π seconds, and F is the intensity of the radiation. The radiation has a maximum value for some definite frequency, and falls off for both higher and lower frequencies. As the temperature is raised the maximum intensity is displaced towards the higher frequencies—the shorter wave-lengths. It is important to explain why it is that these curves have the form they have, and to deduce an expression which will enable one to calculate the energy, corresponding to any frequency, emitted by a black body at any temperature θ. Such an expression, which does fit the experimental results with great accuracy, was deduced by Planck in 1900:



$$F(\nu\,\theta) = \frac{h\,\nu^5}{4\,\pi^4\,C^4}\,\frac{1}{\epsilon^{\frac{h\,\nu}{2\,\pi\,k\,\theta}}-1}$$

C = velocity of light, h and k absolute constants.

To arrive at this result Planck assumed that the radiating body contained elementary " vibrators " which we can now interpret as vibrating electrons. In addition he had to make the assumption that when energy is absorbed or emitted by an oscillator, it is done, not continuously, but in finite, though very small, elements. These energy elements, the energy quanta, the Germans call them—are something of which it is very difficult to form a conception. We have grown used to thinking of elements of matter: I have tried to show at the beginning of this lecture that we may be forced to conceive of elements of electricity not associated with matter, but I am not going to try to convince you of the possibility of thinking of energy—wholly dissociated from either matter or electricity—flying around in discrete elements. Of course if we find that this hypothesis does explain phenomena that none of our usual views explain, and in addition explains all that is explained by our present views, then we shall be forced to accept the energy-quanta as a working hypothesis. Now, in the first place, Planck has recently shown

that his radiation formula can be deduced on the assumption that radiant energy is continuously distributed through space in wave motion, but that a vibrator, when it emits energy, does so in finite elements, although it absorbs energy continuously. It does not seem wholly improbable that a model for an atom can be thought of which will behave in just this way, and if this can be shown the conception of the energy-quanta will be unnecessary so far as accounting for the radiation law is concerned. There can be no question about the energy-quantum hypothesis explaining certain phenomena—especially in connection with the specific heat of bodies, and the photo-electric effect, that have never received any other explanation. But it is by no means certain that this hypothesis is necessary to explain these phenomena. Aside from the difficulty of conceiving of these energy-quanta there is one very serious difficulty in accepting this hypothesis. In accepting it we are obliged to give up the wave theory of light. We should have to go back to what amounts to Newton's corpuscular theory of light, Newton's corpuscles being replaced by these particles of energy. Now so far as we know, such a theory cannot account for some of the most striking properties of light—interference, diffraction, polarization—things which the wave theory of light explains so beautifully. The success of the wave theory of light, not only in explaining known phenomena, but in predicting new phenomena, has been so great that the energy-quantum hypothesis requires very much more evidence in its favor than has yet appeared, before it can be accepted.

Positive Electricity

I now wish to speak about one of the most puzzling features connected with our present views. It has to do with the nature of positive electricity. Negative electricity, we have seen, may be regarded as having an atomic structure, being composed of discrete particles, called electrons or corpuscles. And I have tried to convince you that these corpuscles have a real existence, as real as anything we know about. Negative corpuscles, whatever their origin, all are identical, save for differences in their velocities. One would rather expect to find something similar for positive electricity. But nothing of the sort has ever been found. Positive electricity, whenever it appears, is always associated with atoms or molecules of the chemical elements. We have already spoken of a sphere of positive electricity, but this was introduced solely for the purpose of enabling us to build up an atom of

ordinary matter out of electrons—we had to assume some means of holding the negative electrons together, to keep them from repelling each other by the forces between like charges.

So far, we have become acquainted, in nature, with positive electricity, only in the alpha particles; measurements of e/m and e for them showed them to be atoms of helium with two elementary positive charges. And we also have more direct evidence that the alpha particle on losing its charge becomes an atom of helium. We must now speak of some other occurrences of positive electricity. As from radioactive substances both negative and positive charges are emitted, so in vacuum tubes, when an electrical discharge is maintained in them, we find both cathode rays, which are formed of negative particles, and the anode rays, which are formed of positive rays. If the cathode is perforated with a number of holes, a luminosity is observed behind it. Experiment shows that this luminosity is caused by a stream of positively charged particles, and determinations of the ratio e/m for these particles have been made by methods similar to those employed for the cathode particles. The results of measurements of this kind show that e/m is very much smaller for these positive particles than for the negative corpuscles. This may be interpreted either by assuming that the charges the positive particles carry are much smaller than the charges carried by the corpuscles, or that their mass is very much greater. Now, no negative charge has ever been found smaller than the charge carried by the corpuscle. It seems reasonable to suppose, therefore, that this is also the smallest positive charge that can exist. Assuming this, the observed values of e/m give values for the masses of the positive particles which indicate that they are either single atoms of various chemical elements or aggregates of two or more atoms. For example, the largest value of e/m found is just what would correspond to a single hydrogen atom, carrying a single positive charge. With mercury vapor in the discharge tube, values of e/m are found which would correspond to four mercury atoms, with a single positive charge. And atoms of other chemical elements are detected in the same way. Sir J. J. Thomson, who has contributed a large part of our knowledge of these positive rays, regards the method of determining e/m for these particles as an extremely sensitive method of chemical analysis. The presence of minute traces of a gas may be shown—a far less proportion than would be required to make its presence known by spectroscopic means.

The view which these results lead us to take of the atoms of the elements, is, then, this. We assume positive electricity distributed throughout a volume, for simplicity a sphere, of atomic size. In this sphere of positive electricity there are just enough negative corpuscles to neutralize the positive electricity. Such an atom may expel one or two negative corpuscles without necessarily changing its character thereby—that is, it still remains an atom of the same element, but now positively charged in virtue of having lost some of its negative electricity. The corpuscles may subsequently be picked up again, when the atom becomes once more electrically neutral.

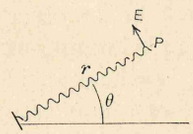
Let me summarize briefly the main points of what I have tried to exhibit. In the first place we considered the negative corpuscle, showing that its mass might be interpreted as resulting from a negative charge in motion, although we were not absolutely forced to this conclusion. The universal occurrence in nature of these corpuscles was next brought out, and their fundamental importance in phenomena connected with light proved; the energy-quantum hypothesis was next briefly touched upon, showing why it had been introduced. Finally the nature of positive electricity was discussed, leading to a provisional view of the structure of the atom.

LECTURE V

Before beginning on the subject announced for this lecture I must, in order to answer questions that have been raised, give a little further account of some of the things dealt with in the previous lecture. You will remember that I described a model of an atom, consisting of a sphere of positive electricity, with a single negative electron moving in a circle inside. The question is, why is it that this emits light? We believe now in the electromagnetic theory of light, according to which light consists of a periodic electric force and a periodic magnetic force, at right angles to each other, propagated by wave motion in a direction at right angles to both the electric and magnetic force. A mathematical calculation, which it would take too long to give here, shows that for points which are at a great distance from the vibrating electron compared to the dimensions of its orbit, this is just the state of affairs that we have—magnetic and electric forces, perpendicular to each other, propagated outwards in waves with the velocity of light. It may puzzle you to understand why it is that the velocity of light enters into the solution

of a purely electrical problem like this. It is because we measure electric and magnetic forces each in a particular set of units—in a problem like the present one, where both electric and magnetic forces enter, they must be reduced to the same system of units. This requires the introduction of a factor, which experiment proves is equal to the known velocity of light in space. Theory shows that the electromagnetic effects are propagated with a velocity equal to the ratio of the units in the two systems, and this ratio is the velocity of light.

A convenient way of thinking of these effects is in terms of lines of force, which we may imagine are carried by the electron, are, in fact, a part of it. Think of these lines of force as so many stretched threads, one end of each attached to the electron. We must assume that transverse waves travel along these strings with the velocity of light. Now suppose that the electron moves in a circular orbit. We know that motion in a circle may be compounded of two motions in straight lines perpendicular to each other. It is only the component at right angles to the line of force which is effective in causing its transverse vibrations, and so we may neglect the other component. Therefore at any point at a distance from the electron the line of force will vibrate back and forth in a direction perpendicular to itself when at rest. The sketch herewith illustrates roughly the spreading out of the transverse electric force along one line of force. We therefore have a vibrating electric force, which at every point is perpendicular to the line joining the electron to the point. Accompanying this there is a magnetic force perpendicular both to the line joining the electron to the point and to the electric force. This therefore results in a spherical wave of electric and magnetic force spreading out from the electron.



METALLIC CONDUCTION

Let us now consider what influence the discovery of the electron has had upon our views of the conduction of electricity through metals. First of all it may be well briefly to consider our previous notions of metallic conduction. It had to be assumed that electricity was something—a substance or an effect—that travelled freely through conductors. The force driving the electricity was called the electromotive force and the flow of electricity, the

electric current. Between these two quantities a simple relation, Ohm's law, was found to hold, which we may express by

$$i = k E$$

or, in words, the electric current is equal to the conductivity k, times the electromotive force. The conductivity k is a specific constant for each kind of conductor. Experiment shows, however, that the conductivity of a conductor is not constant, but depends on its physical state. Thus on heating the conductor, in general, the conductivity diminishes; some metals shows the opposite effect, and this makes it possible to make alloys whose conductivity varies very little with the temperature. In a magnetic field, again, the conductivity may increase or decrease, depending on the conductor and the direction of the magnetic force with respect to the current. Light falling on certain conductors, notably selenium, changes very decidedly their conductivity. Then, too, there was found to be a very close connection between the electric conductivity and the heat conductivity of metals. The old view of an electric current offered no explanation of this variation of conductivity with the physical state of the conductor. It merely had to be accepted as a fact. The best conductors of heat were found, in general, also to be the best conductors of electricity. There was no explanation of this fact on the older view. It is true that Wilhelm Weber towards the beginning of the last century offered an hypothesis in regard to the electric current in which the current was regarded as the flow in opposite directions of positive and negative electric particles, and by making additional hypotheses in regard to the nature of these particles many of the known phenomena might be accounted for. But as long as there was no evidence of the reality of these particles this view never received general acceptance, nor was developed to any considerable extent.

We are still far from being able to give a completely satisfactory explanation of the various phenomena with which we are concerned, but a considerable amount of progress has been made in applying the notion of electrons to metallic conduction, and I shall attempt to give some account of this in its simpler aspects.

The view we have been led to take of an atom is that it is a volume of positive electricity containing many negative electrons. Now we have good reasons for believing that in a metal, in addition to the electrons contained in its atoms, there are also many electrons not contained in them, but continually moving about

among the atoms. We may look upon these electrons, the free electrons we shall call them, as pursuing zig-zag paths among the metallic atoms, colliding with them—perhaps entering into them, while others are shot out from the atoms. On the average there will be a certain number, N, of these free electrons per unit volume. These have a perfectly irregular motion, there are just as many moving in one direction as another. Now suppose an electric force is applied to the conductor. This we know causes a current to flow through it. Let E be the electric force. There is now a force $e E$ acting on each electron driving it in a direction opposite to the direction of the electric force. Negative electricity flowing in one direction is equivalent to positive electricity flowing in the opposite direction. We thus get an electric current flowing in the direction of the electric force. It is worth while to calculate the strength of this electric current on the simplest view we can take. Let v be the velocity of the electrons before the electric force was applied. The velocity of an electron in a direction opposite to that of the electric force is given by

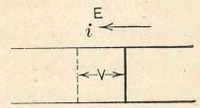
$$m \frac{d^2x}{dt^2} = e E$$

$$\frac{dx}{dt} = \frac{e}{m} E t$$

at any time between two collisions of the corpuscle. But at the beginning of the free paths the corpuscles had no average velocity in this direction; at the ends of their free paths the electrons thus have a velocity $e/m\ E\ T$ where T is the time the electron is free. So the average velocity in this direction is

$$\frac{1}{2} \frac{e}{m} T E = V$$

In a unit volume of the metal we have N free electrons; each carries a charge e, and each moves with this average velocity in a direction opposite the electric force. Therefore the electric current is equal to all the charges that cross the section of the conductor in unit time. Let the cross-section of the conductor have unit area. Then the number of electrons which cross it in unit time will be equal to the number that at the beginning were contained in the volume V, *i.e.*,



$$\frac{1}{2} \frac{e}{m} T E N$$

Each has a charge e, so that the current is

$$i = \frac{1}{2}\frac{e^2}{m} T N E$$

We thus get Ohm's law, the conductivity being

$$k = \frac{1}{2}\frac{e^2}{m} T N$$

Let us now introduce an hypothesis which we shall attempt to justify by its consequences. It is that the electrons move about among the atoms of the metal just as the molecules of a gas move about, and just as the average kinetic energy of a molecule of a gas is proportional to its absolute temperature, θ,

$$\frac{1}{2} m v^2 = \alpha \theta$$

so the average kinetic energy of an electron is proportional to the absolute temperature, with the same factor of proportionality, α.

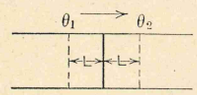
Then since $T = \frac{L}{v}$, where L is the average distance the electron goes between collisions—the free path of the electron—we can write

$$k = \frac{1}{2}\frac{e^2 L}{m v} N = \frac{e^2 v N L}{4 \alpha \theta}$$

Experiment shows that the conductivity of most pure metals varies very nearly inversely as the absolute temperature. This is what our formula tells us, provided that $N L v$ does not vary with the temperature. On our hypothesis, v varies as the square root of the temperature, so that we may assume that NL varies inversely as the square root of the temperature. We have not time to consider the different views that have been held on this matter; the point I wish to emphasize is that the view of metallic conduction that has been briefly described, does lead, first of all, to Ohm's law, and it does account for a variation of conductivity with the temperature. The old idea of the electric current made no attempt to give any explanation.

Let us now find the conductivity for heat of our metal. For this purpose we must calculate how much heat goes through any unit cross-section in a unit time. Let the temperature decrease

as we go from left to right. The number of electrons that cross any cross-section in unit time is $\frac{1}{6} N v$. For v is the distance they travel in unit time and as they move in all directions one-sixth of those in a volume v will get through. Each electron has an amount of energy $\frac{1}{2} m v^2 = \alpha \theta$. For θ we must take the temperature at the last collision. On the average, the last collision was at a distance L to the left of A. Call the temperature at this place θ_1. Hence the heat crossing A in unit time from left to right is



$$\frac{1}{6} N v \alpha \theta_1$$

Similarly the heat crossing A from right to left is

$$\frac{1}{6} N v \alpha \theta_2$$

Hence the net amount of heat that crosses A from left to right is

$$\frac{1}{6} N v \alpha (\theta_1 - \theta_2)$$

or

$$\frac{1}{3} N v \alpha \frac{\theta_1 - \theta_2}{2 L} L$$

$\theta_1 - \theta_2$ is the difference in temperature at two places distant $2 L$ from each other; $\frac{\theta_1 - \theta_2}{2 L}$ is therefore the rate of fall of temperature as we go along the bar. Hence the heat conductivity is

$$c = \frac{1}{3} N v \alpha L$$

The ratio of the electric to the heat conductivity is

$$\frac{c}{k} = \frac{4}{3}\frac{\alpha^2}{e^2} \theta$$

This result is of particular interest because the only quantity in it which can vary with the temperature is θ, the temperature itself. The ratio of the heat to the electric conductivity should then increase proportionately to the absolute temperature. Suppose we put in the known values of the quantities in this equation.

We have found that

$$e = 1.6 \times 10^{-20} \text{ in electromagnetic units.}$$

Now α is known from the kinetic theory of gases. It is equal approximately to

$$1.8 \times 10^{-16}$$

Then at 0 deg., $\theta = 273$

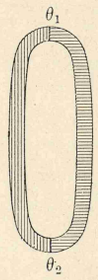
$$\frac{c}{k} = 4.6 \times 10^{10}$$

Experiment shows that this ratio, for a large number of metals, is about $6 - 7 \times 10^{10}$. In our calculation, it has been assumed that both the thermal and electric currents are carried only by the negative corpuscles. It is almost certain, however, that the thermal conductivity is partly due to the motion of the atoms themselves inside the metal. This would tend to increase the ratio c/k, bringing it nearer to the known value determined by experiment.

This result is as remarkable as those obtained by the application of the theory of electrons to optical phenomena that we considered in the last lecture. It furnishes very strong confirmation of the view that the electron plays an important part in electric conduction in metals.

Thermoelectric Effects

If a circuit is made of two different metals, and the two junctions are kept at different temperatures, it is known that a current will flow around the circuit. Let us see how the corpuscular theory accounts for this effect. We have taken the view that the corpuscles move about in a metal just as molecules of a gas in an enclosed space. And just as the pressure which a gas exerts is a result of the impacts of the molecules, so there will be a pressure at any point in a metal due to the impacts of the corpuscles. To calculate this pressure we need only to consider the momentum which the corpuscles bring up to a unit area in unit time. On the average we can say that one-sixth of all the corpuscles are moving in a given direction. Each has momentum $m v$. The momentum of the corpuscles striking a unit area of the wall in unit time will therefore be



$$\frac{1}{6} m v^2 N$$

If we assume that the corpuscles are reflected from the wall without loss of energy, each carries away an amount of momentum $m v$, but in the opposite direction from that it brought up to the wall. Therefore the wall receives in unit time the momentum

$$\frac{1}{3} m v^2 N$$

But this must be the pressure the corpuscles exert. Hence

$$p = \frac{1}{3} m N v^2 = \frac{2}{3} N \alpha \theta$$

If now the number of free corpuscles in unit volume is different for different metals, at a junction between two metals there will be a difference in the pressure of the corpuscles on the two sides and so the corpuscles will move from one metal to the other. To make the case definite suppose that N_1 is greater than N_2 and θ_1 is greater than θ_2. Then at the hot junction there will be a difference in pressure of

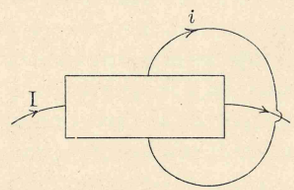
$$\frac{2}{3} (N_1 - N_2) \alpha \theta_1$$

driving the corpuscles from 1 to 2. At the other junction there will be a difference in pressure

$$\frac{2}{3} (N_1 - N_2) \alpha \theta_2$$

also driving the corpuscles from 1 to 2. But this is less than the former difference in pressure and so there will be a continual flow of corpuscles from 1 to 2 at the warm junction and from 2 to 1 at the cool junction. There will be therefore an electric current flowing in the opposite direction.

The other thermoelectric effects—the Peltier effect, the Thomson effect—may be explained qualitatively equally well by the corpuscular theory.



Let us now consider some effects of magnetism on electric conductivity. According to the views of Maxwell, if a conductor carrying an electric current is placed in a magnetic field a mechanical force is exerted on the conductor, but there is no effect on the electric current.

It was discovered by Hall that if the conductor were in the form of a thin plate, through which a current I was sent in the direction indicated, and a magnetic force applied perpendicularly to the plate, then a current was produced in the circuit i. With no magnetic force acting, there is no current in this circuit. The existence of such a transverse current can easily be accounted for on the corpuscular view. Acting on a corpuscle there is a force at right angles both to the direction of the magnetic field H, and to the direction of motion. This force deflects the corpuscles from the right to left motion so that some of them move through the branch circuit, thus producing an electric current in the opposite direction. We meet, however, with a difficulty here.

According to what we have just seen, the Hall effect should have the same sign for all metals. But as a matter of fact for some metals the transverse current has the direction indicated by this theory; for other metals the transverse current has the opposite direction. This variability could be accounted for if we assumed that, in addition to the negative corpuscles, the current was also carried, in part, by positive charges; these would result in a transverse current opposite in sign to the current carried by the negative corpuscles and so, depending upon which effect was the greater, the Hall effect would have one sign or the opposite. But we have very strong evidence that positive charges are always associated with atoms and so we cannot assume them to have mobility enough in a metal or other solid to take an appreciable part in electric conductivity. We must therefore seek another explanation. The explanation is to be found, I think, in the structure of a metal. We have assumed far too simple a structure for the interior of a metal. In our calculations we have considered only the free electrons—that is, those that are outside of the atoms. It is probable that the corpuscles in the atoms play a part in these effects, although we have no theory yet which will account quantitatively for experimental results.

A similar difficulty is met when we attempt to account for the change in the conductivity of a metal when in a magnetic field. If the magnetic force is applied at right angles to the direction in which the electric current flows, then as a result of the deflections of the paths of the electrons it is easily seen that the conductivity of the metal will be decreased. This is the result that is observed, except that with the magnetic metals, iron, nickel and cobalt,

weak magnetic fields decrease the conductivity; but on increasing the magnetic force the effect changes in sign, so that with strong fields the conductivity is increased. On this simple view there should be no effect on the conductivity when the magnetic force is parallel to the current. Experiment shows, however, that, in general, there is a decrease in the conductivity in this case. Qualitatively, both these departures from our simple theory can be explained by assuming that the effect of the magnetic field is to produce a rearrangement among the atoms so as to alter the free paths of the electrons. That some such effect should exist is probable. Recent work in metallography has shown that metals have a very complicated structure—being in fact aggregates of crystals. The view we have taken of a metal is undoubtedly far too simple and it is much more to be wondered at that this simple view should lead to so many striking confirmations than that departures from it are observed.

A number of attempts have been made to explain magnetism on the electron hypothesis. At first sight it seems an easy thing to do. We generally look upon a magnetized body as an assemblage of small magnets which are all made to turn more or less in one direction when a magnetic force is applied. Now the fundamental theorem in electromagnetism is that an electric current flowing in a small closed circuit is equivalent, as far as external effects go, to a small magnet, whose axis is perpendicular to the plane of the current. As an electron in motion is equivalent to an electric current, the electrons circulating in closed orbits inside the atoms might be expected to make the atoms themselves elementary magnets. This would be just the result necessary to account for the magnetism of such substances as iron and also the so-called para-magnetic substances—which have similar magnetic properties but in a much smaller degree. However, when one considers the possible symmetrical distribution of electrons in the atoms, it found that the atoms will not be elementary magnets. There will still be an effect arising from the magnetic field on the motion of the electrons inside the atoms and such as to correspond to diamagnetism—the property exhibited by copper and many other substances. The difference between paramagnetism and diamagnetism may be shown by taking two rods—one of iron and one of copper, suspended in a uniform magnetic field. The iron tends to set itself so that its length is along the direction of the magnetic force, while the copper tends to set itself at right angles to the magnetic force. Thus, on this

view, the atoms of all substances would be diamagnetic. To account, then, for paramagnetism, it is necessary to assume that the atoms, owing to a lack of symmetry, are effectively elementary magnets, as a result of the circulating electrons. The theory has been developed along these lines by Langevin, who finds that the diamagnetism will be independent of the temperature while paramagnetism varies inversely as the temperature; and this agrees, in general, with experimental results. We thus have every reason to believe that a real explanation of magnetism is to be found in the electron theory.

It will not be out of place here to say a word regarding the essential difference between a conductor of electricity and an insulator. In a conductor we have seen that we may assume that, in addition to the electrons circulating in the atoms, there are also free electrons. A metal atom may be looked upon as one from which one or two electrons can escape, and these escaped electrons then become free electrons. An atom of an insulator, on the other hand, we may regard as one in which the electrons are more firmly held, so that in a perfect insulator there will be no free electrons.

At the beginning of these lectures I told you that I was going to try to show how far recent discoveries had changed our old ideas about the constitution of matter. It may therefore be well to give a very brief summary of the most important results.

In the first place we have learned that the atoms of the various chemical elements are complicated structures. One constituent which is common to all atoms is the negative electron or corpuscle. In addition we have to assume positive charges as well—as to what their nature is we are still very much in the dark. As for the number of corpuscles in the atom, various lines of reasoning give results that show that this number must be comparable to the atomic weight of the atom. One method of getting an estimate of the number of corpuscles in an atom is by calculating the absorption that a stream of beta particles undergoes when traversing a known thickness of matter. This is something that can be determined experimentally, and by assuming that the absorption of beta particles is the result of collisions with the corpuscles in the atoms, an estimate of the number of the latter may be obtained. So that we cannot assume the whole mass of an atom to be the sum of the masses of the electrons contained in it. We are led, therefore, to assume that the mass of the atom is concentrated in the positive part of the atom. We may take a

provisional view of the atom something like this—a number of positive charges with just enough negative corpuscles circulating around them to neturalize the electric charge. Atoms built in this way will have different degrees of stability. Such an atom may lose or gain one or two corpuscles and still remain the same kind of an atom. It will then correspond to a very stable element. Or an atom may be so unstable that on losing an electron a complete rearrangement takes place, resulting in a wholly different atom. That will correspond to a radioactive atom. This view of the atom leads to a natural explanation of chemical combination. Say that we have two different atoms A and B. A may lose an electron, leaving it positively charged. B may gain the electron lost by A. B is then negatively charged. A and B will then be attracted to each other and they may combine to form a molecule of two atoms $A\ B$.

The weakness in the position where we stand at present lies in our ignorance of the nature of positive electricity. Negative electricity distributed in corpuscles, we know a great deal about. We have seen something of the universal importance of the negative corpuscle in optical, thermal, and electric phenomena.

We have seen that the mass of the negative corpuscle may be interpreted in terms of an electric charge in motion, that its mass increases with increasing velocity. So we are led to think that perhaps all mass is electrical in its nature. We cannot, however, have much confidence in this view until something analogous is proved for the unknown positive charge.

Besides the change in our ideas regarding atomic structure which has resulted from the study of radioactivity, there is another much more revolutionary trend in modern thought concerning the physical universe. This has to do with the very foundation of the science of mechanics. If what has apparently been proved for the negative corpuscle, that its mass increases with its velocity, holds for all matter, then our familiar laws of mechanics, which have been accepted as holding absolutely, can be regarded only as approximations. It is only when the velocities we consider approach that of light that there will be any appreciable departure from the motion given by applying Newton's laws. According to our usual ideas, if a constant force acts on a body, a certain definite momentum, the product of the mass by the velocity, will result. If the force acts twice as long, double the momentum will result. The mass being constant, there will be no limit to the velocity that the body may acquire.

It is only necessary to apply the force for a sufficiently long time. But this is not so if the mass increases with the velocity. Doubling the time the force acts will not double the velocity, since the mass also increases. In the case of a corpuscle, when we regard its mass as resulting from a charge in motion, the mass becomes infinite when its velocity is equal to that of light. If the same be held to be true for all matter, if, in other words, all mass is of an electromagnetic origin, then the velocity of light is the highest velocity we can conceive of. This is a result which is startling when viewed from the standpoint of our usual ideas of mechanics. According to this view, the velocity of light in space is a constant of fundamental importance in the whole domain of the physical sciences.

All of this is intimately related to what has come to be known as the principle of relativity. If it is assumed that the velocity of light in space is the highest velocity that can be attained, it must be impossible to detect absolute motion of a system by any experiments made in that system. Suppose, for example, the velocity of light be measured on the earth, first in the direction in which the earth is moving about the sun, and second, in a direction at right angles to the motion of the earth. In the former direction the velocity of the earth would be added to the velocity of light, and the sum would be a velocity greater than that of light. But this, by hypothesis, is impossible. Hence it would follow that by no experiment in a moving system can we detect the absolute motion of that system. All that can be detected is the motion of one system relative to another.

A number of experiments have been made with the object of detecting absolute motion. The best-known of these is the Michelson-Morley experiment, in which a difference in the velocities of light, traveling along and perpendicular to the motion of the earth, was looked for. All such experiments have given negative results. And these negative results have led to the enunciation of the principle of relativity, according to which the absolute motion of a system cannot be determined by any experiment made in that system. In this form, the principle of relativity is a principle of negation, like two other fundamental physical principles—the principle of the conservation of energy and the second law of thermodynamics. The former denies the possibility of perpetual motion, and the latter denies the possibility of transferring heat from a cold to a hot body by any self-acting mechanism.

From a certain point of view, the principle of relativity, stated in this way, would seem to be a necessary consequence of the electromagnetic origin of mass. If all matter can be considered to result from the motion of electric charges, it must follow that absolute motion cannot be determined. For without motion, there could be no matter, and without matter there would be no possibility of detecting motion.

However, the necessity of introducing the principle of relativity with all of the consequences, so opposed to what we have always assumed as fundamental truths, that have been held to follow from it, cannot be said to be proved. Speculation regarding it has proceeded rather farther than experimental results warrant. The subject is mentioned here only for the purpose of showing how deeply into our fundamental conceptions of the physical universe the study of radioactivity has led.

In conclusion, let me repeat what may be taken as the main results of the study of radioactive phenomena. First, we are forced to believe that the atoms of the elements are dynamical systems of varying degrees of stability. In the second place, the negative corpuscle, or electron, has been shown to be of fundamental importance in the whole domain of the physical sciences. The difficulties in developing further these views of matter, for which a foundation has been laid, center about two large problems: the nature of positive electricity, and the old problem of the ether.